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High Performance Commercial Building Systems

Manual of Procedures for Calibrating Simulations of Building Systems

Element 5 - Integrated Commissioning and Diagnostics
Project 2.3 - Advanced Commissioning and Monitoring Techniques

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MANUAL OF PROCEDURES FOR CALIBRATING SIMULATIONS OF BUILDING SYSTEMS

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EXECUTIVE SUMMARY

The calibration of a cooling and heating energy simulation for a building to measured heating and cooling consumption data has been shown to be valuable for predicting the energy savings possible from operational changes and retrofits. It is also recognized as an important way of baselining energy consumption to determine savings from retrofits. However, the calibration processes used to achieve agreement have generally been quite time-consuming.

This manual presents a methodology for the rapid calibration of cooling and heating energy consumption simulations for commercial buildings based on the use of "calibration signatures", that characterize the difference between measured and simulated performance. The method is described and then its use is demonstrated in two illustrative examples and two real-world case studies. This document contains characteristic calibration signatures suitable for use in calibrating energy simulations of large buildings with four different system types: single-duct variable-volume, single-duct constant-volume, dual-duct variable-volume and dual-duct constant-volume. Separate sets of calibration signatures are presented for each system type for the climates typified by Pasadena, Sacramento and Oakland, California.

I. BACKGROUND AND OVERVIEW

1. Calibrated simulation

Need for Calibration

Energy simulation has been an important part of building science research, as well as implementation of energy efficiency improvements. Available simulation tools include detailed whole building simulations (such as DOE2 and BLAST), detailed system simulations (HVACSIM+) and simplified models (ASEAM and AirModel). Historically, the inputs for energy simulations of commercial buildings have been based on design data. The experience of the authors and others who have performed hundreds of energy simulations indicates that differences of 50% or more between simulation results based on design data and measured consumption are not unusual. These errors are not thought to be due to errors in the simulation software itself, but to errors in the input assumptions for a particular building, due to misunderstanding of the building's design or to the differences between design and as-built conditions or operations.

Consequently, numerous organizations and individuals have developed procedures to adjust the inputs used to "calibrate" a simulation so the simulated results more closely match measured consumption (e.g. Diamond and Hunn 1981, Kaplan et al. 1992, Haberl and Bou-Saada 1998 and Liu and Claridge 1998). These procedures employ a variety of techniques to either measure or infer the characteristics of individual buildings as they were built and operated and identify candidate changes in model inputs that may resolve the differences. These efforts have been quite successful in achieving simulated results that agreed with the measured consumption, typically to less than 5% on an annual basis. Agreement within 5-10% has often been achieved on a monthly basis, and sometimes on a daily basis. Once a probable error (or errors) in a simulation input has been identified, the analyst must typically assess whether the change makes physical and intuitive sense. This sometimes requires revisiting the building or conducting some other investigation. It must then be decided whether it is appropriate to revise the model inputs before accepting the model.

Uses of Calibrated Simulation

The calibration processes used to achieve agreement have generally been quite time-consuming and required a great deal of specialized expertise. There would be tremendous value in having a procedure that can quickly and reliably calibrate simulations of large commercial buildings with built-up HVAC systems. Then, it would be practical to use a calibrated simulation for many different uses. There has been an increased level of interest in applications for calibrated simulation in recent years (IPMVP 2001, Liu and Claridge 1998). Uses for calibrated simulation include:

- energy audits, to determine the potential savings from proposed retrofit measures;
- energy savings determination after retrofits
- energy savings estimation, to explore the potential savings from changing building operational strategies ("what-if" analysis);
- existing building and new construction commissioning;
- fault detection and diagnostics
- model-based optimization; and

- program evaluation.

Calibrated simulation received a significant boost by inclusion as one of the approved methods for establishing energy baselines for savings determination in the *International Performance Measurement and Verification Protocol* (IPMVP 2001).

Data Used for Calibration

A simulation that will be useful for large commercial buildings with built-up HVAC systems can require hundreds of input variables, and will have at least a few dozen crucial input parameters. If monthly values of measured consumption data were used for calibration, there would be more parameters that may be varied than the number of data points being fit with a typical year of data and the problem would be mathematically "over-determined" (more equations than unknowns). This has the consequence that the calibration achieved might fit past data very well, but will not necessarily fit future data very well. Hence, a calibration based on monthly data is not suitable for use in tuning HVAC operating parameters. The use of several months of daily consumption data eliminates this problem and has been shown to be suitable for use in calibrating models that were subsequently used to develop improved operating strategies (Liu and Claridge 1998). Hourly data can also be used, although dynamic effects of the thermal mass of the building and system will become evident. In some calibration methods, this could present a problem, although the differences will tend to average out over the course of a day, so some statistical analysis will not be affected by these differences. Hourly data can also be used to "fine tune" a calibration that was done mostly with daily data (Liu, Wei and Claridge 1998). This is achieved by introducing a daily load profile as shown in the two case studies in this report.

The simulation period should cover most of the annual ambient temperature range. It may vary from several weeks to a whole year depending on the fluctuations of weather conditions throughout the year.

The measured performance data used for calibration must closely match the simulated data when calibration is complete. It must include the same physical factors (e.g. thermal load or energy consumption, whole building or system-based, hourly, daily or monthly) over the same period of time. Often, either the measured or simulated data can be aggregated or disaggregated in order to perform the necessary comparison. Measured data can be obtained from any of a number of sources:

- Utility billing data (typically monthly, or something close to monthly).
- Utility interval meter data (available from the utility for some larger buildings).
- Interval pulse-data obtained from a utility meter.
- Data from an Energy Management and Control System.
- Data from an installed data logger (with Btu or kWh sensors/transducers).

Data quality must be assessed for any use of measured data. Identifying erroneous data points is important. Particularly for shorter interval data, an approach to identifying and "fixing" any erroneous or missing data must be designed: in some cases, it is appropriate to interpolate to fill any holes in the data, while in other cases it is best to simply eliminate those data points from the analysis.

2. Overview of the calibration signature method and this manual

This manual presents an improved method of calibrating simulations – the calibration signature method. Experienced users of the method can calibrate a two-zone simulation of a building with large built-up systems in 10-40 hours. The approach has also been used by students to complete calibrations as course project assignments in a graduate building systems course at Texas A&M.

The method is based on a unique graphical representation of the difference between the simulated and measured performance of a building, referred to as a "Calibration Signature". For a given system type and climate, the graph of this difference has a characteristic shape that depends on the reason for the difference. For example, for a single-duct variable-air-volume system in Pasadena, if the cooling coil temperature is one degree lower in the real building than was assumed in the simulation, the shape of the calibration signature will look very similar to the graphs shown at the top of Appendix D-1. These "characteristic" calibration signatures (or "characteristic signatures") can be produced for a given system type and climate and published. By matching the observed signature with the published characteristic signature, the analyst is given clues to the factors that may be contributing to the errors he or she is observing.

This manual describes the use of the calibration signature method. It shows how the calibration signature is defined and how it can be calculated for a given building. It describes how characteristic signatures were derived for a set of system types and climates. The process for using these characteristic signatures as an aide in calibration is then described. A series of examples help to describe the use of these signatures and to illustrate some of the decisions that must be made. In the Appendices, characteristic calibration signatures are presented for the following system types and climates.

System Types:

- Single-Duct Constant-Air-Volume (SDCV).
- Single-Duct Variable-Air-Volume (SDVAV).
- Dual-Duct Constant-Air-Volume (DDCV).
- Dual-Duct Variable-Air-Volume (DDVAV).

California Climates:

- Pasadena.
- Sacramento.
- Oakland.

II. CALIBRATION USING CHARACTERISTIC SIGNATURES

The calibration procedure presented in this manual is based on the use of "characteristic signatures". Wei et al. (1998) found that calculating the difference between the measured heating or cooling consumption and that predicted by an un-calibrated simulation, normalizing them and plotting them as a function of ambient temperature, provides important information about the input variable change(s) needed to achieve calibration. This type of plot has been termed a "calibration signature". By publishing characteristic signatures, a useful clue is provided to anyone intending to calibrate a simulation.

This section presents the definitions of the calibration signature, the characteristic signature, and two statistical variables used to evaluate calibrated simulations. It also presents a detailed step-by-step calibration procedure and a description of the published characteristic signatures and their climate dependence.

1. Definition of the calibration signature

The calibration signature is a normalized plot of the difference between measured energy consumption values and the corresponding simulated values as a function of outdoor air temperature. This is typically calculated on a daily average basis, but other time steps can be used as well. The energy consumption values can be whole building or system consumption, and they can be electric (kWh) or thermal (e.g. chilled water consumption in MMBtu). The calibration signature value for heating or cooling energy consumption is calculated as follows:

$$\textit{Calibration signature} = \frac{-\textit{Residual}}{\textit{Maximum measured energy}} \times 100\ \% \qquad (1)$$

where

$$\textit{Residual} = \textit{Simulated consumption} - \textit{Measured consumption} \qquad (2)$$

and the denominator is the maximum measured cooling or heating consumption, respectively for a cooling or heating calibration signature, determined over the entire range of outside air temperatures contained in the data file being used.

Figure 1 shows a calibration signature plot for hot water (HW) energy use. Note that this signature always has positive values, it decreases with increasing outside air dry-bulb temperature (T_{db}) and reaches zero at about 80°F. These characteristics will be useful in trying to determine what errors were present in the simulation inputs.

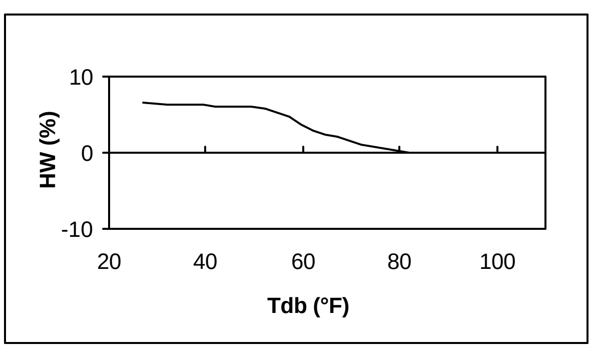


Figure 1. Example of a heating calibration signature

2. Definition of the characteristic signature

Any particular uncalibrated (or partially calibrated) simulation will have a calibration signature, as described in the previous section. However, the errors in the simulation inputs that are responsible for the residuals between measured and simulated data will cause a predictable shape for the calibration signature. If you compare the results from your simulation with a published calibration signature, and its shape matches, you will have found a clue in what simulation input parameter to change to improve your simulation.

These characteristic calibration signatures can be calculated using simulation programs. This is done by simulating the building with one value for an input parameter (the “baseline” run), then changing that input parameter by a given amount and rerunning the simulation. The “residuals” between these two simulations are calculated, normalized, and plotted versus outdoor air temperature, just as was done to calculate a calibration signature for a particular uncalibrated simulation with measured data. The formula for calculating this characteristic calibration signature is as follows:

$$\textit{Characteristic signature} = \frac{\textit{Change in energy consumption}}{\textit{Maximum energy consumption}} \; x\ 100\ \% \qquad (3)$$

where the change in energy consumption is taken as the cooling or heating energy consumption value from the simulation with the changed input minus the baseline value at the same temperature. The denominator is the maximum baseline cooling or heating consumption, respectively for a cooling or heating characteristic signature, determined over the entire range of outside air temperatures contained in the weather file being used.

This definition then shows all changes in terms of the percent change relative to the maximum value of the cooling required in the baseline case for the cooling characteristic signature, or the maximum baseline heating consumption for the heating characteristic signature. These signatures also represent a parametric sensitivity analysis for the building and system of interest.

Figure 2 shows cold deck temperature (T_c) characteristic calibration signatures for cooling and heating. The curve on the left shows the change in chilled water (CHW) energy use and the curve on the right the change in hot water (HW) energy use, when the temperature at which air leaves the cooling coil was decreased from 55 to 53°F.

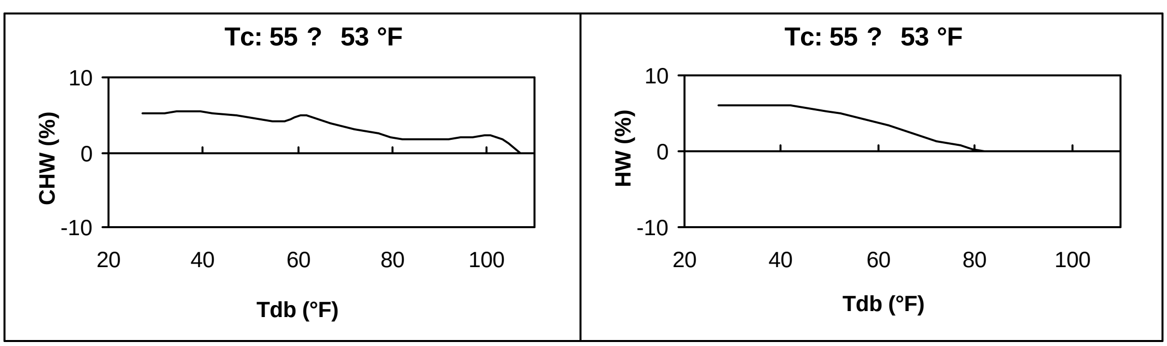


Figure 2. Cold deck temperature characteristic calibration signatures

If we were attempting to calibrate the simulation with the heating calibration signature shown in Figure 1, it is clear that this calibration signature matches the heating characteristic signature in Figure 2, so the best input variable to change is the cold deck temperature. Since the characteristic signature is the result of reducing the coil temperature by two degrees, the temperature used as input for the simulation should also be reduced by about two degrees to eliminate this error.

The clues provided by the characteristic calibration signatures are much clearer when you use both cooling and heating calibration signatures. These two will typically show very different trends, and the combination can be a powerful indicator of the input parameter that needs to be changed.

3. Weather Implications

The characteristic signatures shown in Figure 2 clearly depend on outside temperature. Though not explicitly shown, they also depend on the ambient humidity level when it is high enough to induce latent cooling loads. This is treated by simply using the mean of the humidity values present at each temperature in the weather data for the site in question to define the characteristic signatures. This humidity dependence suggests that separate sets of signatures may be needed for sites with significantly different temperature and humidity combinations. Separate sets of signatures are also required for different air handler types.

Characteristic signatures depend on the correlation between relative humidity and dry-bulb temperature for the location of interest. Figure 3 shows the average measured relative humidity as a function of ambient temperature for the three California cities used to generate the sets of characteristic signatures presented in this manual. The weather data used was provided by Motegi (Motegi, 2001). Dry-bulb temperatures in the data sets used range from 33 °F to 97 °F, 27 °F to 105 °F and 35 °F to 83 °F respectively for Pasadena, Sacramento and Oakland. Relative humidity ranges from 30 to 81%, 22 to 85% and 40 to 91% respectively.

We notice that Sacramento has the widest ranges of both temperature and relative humidity. It is the coldest city in the winter and the hottest in the summer. Oakland has the narrowest ranges of temperatures and relative humidity. It is the warmest in the winter and the coolest in the summer. Pasadena weather conditions fall between the extremes of the weather conditions of the other two cities.

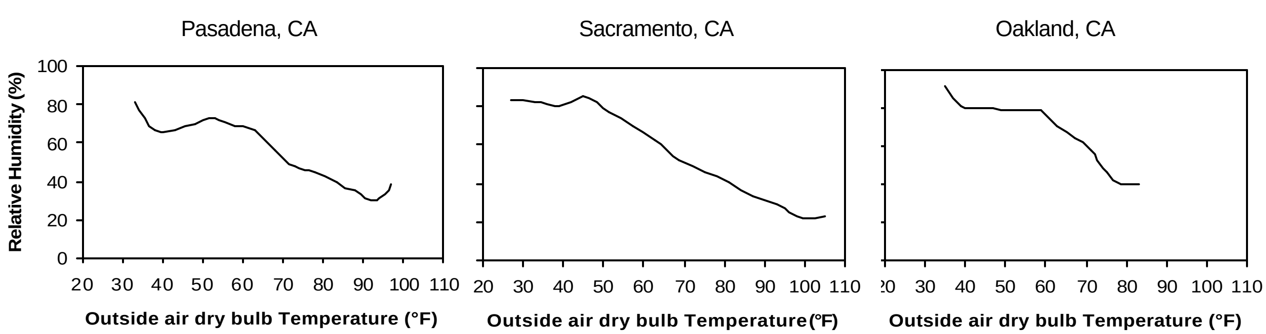


Figure 3. Weather data for three representative California cities

4. Evaluating the Adequacy of a Calibration

There are several metrics to use in evaluating whether or not a simulation is sufficiently calibrated, or in comparing two possible calibration adjustments.

- **Root Mean Square Error (RMSE)**, defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} Residual_i^2}{n-2}} \tag{4}$$

where n is the number of data points. The RMSE is a good measure of the overall magnitude of the errors. It reflects the size of the errors and the amount of scatter, but does not reflect any overall bias in the data. For example, if large errors are randomly distributed both above and below zero, you would have a large RMSE. Similarly, if all the errors are positive, you might have the same RMSE. Thus, the RMSE would be a good metric of how "good" the simulation is for calibration purposes. In the authors' experience, it is generally difficult to achieve a value of the RMSE that is less than 5 to 10% of the mean value of the larger of the heating and cooling consumption. The minimum RMSE will sometimes be significantly larger, particularly when heating and cooling consumption are small relative to total internal gains.

- **Mean Bias Error (MBE)**, defined as:

$$MBE = \frac{\sum_{i=1}^{n} Residual_i}{n} \tag{5}$$

where n is the number of data points. With the MBE, positive and negative errors cancel each other out, so the MBE is an overall measure of how biased the data is. The MBE is also a good indicator of how much error would be introduced into annual energy consumption estimates, since positive and negative daily errors are cancelled out.

A simulation with a small RMSE, but with a significant MBE, might indicate an error in simulation inputs. A simulation with a large RMSE but a small MBE, might have no errors in simulation inputs, but building performance may reflect some other un-modeled behavior (such as occupant behavior) that is difficult to simulate, or it may have significant input errors. Minimizing mean bias error is very important if a calibrated simulation is to be used as a baseline for determining savings from retrofits or commissioning.

Calibration using characteristic calibration signatures involves estimating both cooling and heating energy use. A separate RMSE can be calculated for each. It is common that making a specific change to simulation inputs will increase a heating RMSE while decreasing a cooling RMSE, or vice versa. In this case, the two RMSE values may be summed, and a minimum value may be sought.

5. Published characteristic signatures

This manual provides characteristic signatures for single-duct constant-air-volume (SDCV), single-duct variable-air-volume (SDVAV), dual-duct constant-air-volume (DDCV) and dual-duct variable-air-volume (DDVAV) air handling Units (AHUs). The signatures are given for three representative climates in California: Pasadena, Sacramento and Oakland. The most commonly used AHUs in California appear to be variable-air-volume (VAV) systems. Characteristic signatures for the four major AHU system types are produced and discussed in this manual.

Separate characteristic signatures are prepared for each parameter that has been found to be of major importance in calibrating a simulation, as shown below:

- Cold deck temperature
- Hot deck temperature (DD systems)
- Supply air flow rate (for CV systems)
- Minimum air flow rate (VAV systems)
- Floor area
- Preheat temperature
- Internal gains
- Outside air flow rate
- Room temperature
- Envelope U-value
- Economizer

These parameters were selected as those that have a significant influence on energy consumption, those that are perceived as having a significant influence (and thus are commonly considered for making calibration changes) and those in which the authors have frequently seen errors.

The characteristic signatures in this manual were created by simulating a simple building, and then altering one of the key input parameters and then calculating and plotting their characteristic calibration signatures. Appendix A describes the building and system models that were used to create the signatures.

Sets of characteristic signatures are available in appendices C, D, E and F respectively for SDCV, SDVAV, DDCV and DDVAV systems. Each appendix has sets of signatures for Pasadena, Sacramento and Oakland, California. The left-hand column shows the chilled water (CHW) characteristic signature and the right-hand column shows the hot water (HW) characteristic signature for the input variable noted in each figure.

The characteristic signatures were generated using AirModel, an HVAC software package for simulation of building cooling and heating consumption. AirModel is based on the ASHRAE Simplified Energy Analysis Procedure (Knebel 1983) was developed at the Energy Systems Laboratory at Texas A&M University (Liu et al., 1997). The signatures and calibration methodology may also be used with other simulation packages that can provide daily values of heating and cooling consumption.

In some cases, it may be feasible and preferable for an analyst to create his or her own characteristic signatures, using the simulation to be calibrated as the baseline. This may be a convenient way to summarize the possible adjustments that can be made and to organize a selection process. The process for doing this is described in Appendix G.

6. Calibration using characteristic signatures

The steps to follow to calibrate cooling and heating simulations using characteristic signatures are as follows:

Step 1. Collect measured consumption and weather data over a period of uniform HVAC system operation.

Step 2. Perform an initial simulation using the best estimates of your system parameters.

Step 3. Make any necessary conversions of weather data, measured consumption data and simulated results to daily averages or another time step, or temperature bins. It may be necessary to adopt guidelines to deal with missing measured data (e.g. interpolate up to a critical number of missing data points per time step and disregard the whole time step if more data points are missing).

Step 4. Calculate the residuals, the RMSE and the calibration signature according to equations 2, 4 and 1.

Step 5. Plot measured data, simulated results and residuals in the same chart as a function of outside air dry-bulb temperature and plot the calibration signature on the same or a separate chart. It may be helpful to perform some type of best fit regression to the calibration signature data points to help detect the overall trend of the signature.

Step 6. Compare cooling and heating calibration signatures with the characteristic signatures available in appendices C, D, E or F for the corresponding system type and climate and try to find the best match or matches. If there is a need to create your own characteristic signatures for other weather conditions or other variations of air handling unit types or to test the sensitivity of other input parameters not tested in the signatures provided, follow the procedure described in appendix G. In comparing the pair of cooling and heating calibration signatures with pairs of cooling and heating characteristic signatures, things to look for include intercepts, slopes and bulges. This will identify an input or inputs that, when changed, are the most likely to minimize the residuals over the targeted range or ranges of outside air temperature.

If two or more pairs of characteristic signatures have similar shapes (e.g. the floor area and the total supply air characteristic signatures in appendix C-1), conduct field measurements or use your own judgment to estimate which one is the most likely to be inaccurate in the initial simulation. It's possible that more than one needs to be changed.

If the calibration signatures do not strongly resemble any pair of characteristic signatures, try to use characteristic signatures to reduce cooling and heating calibration signatures at their maximum magnitudes or to remove any irregular shapes in either calibration signature over a certain range of outside air temperature. It is possible to alter two or more inputs simultaneously when each one of them targets a different range of outside air temperature or targets more specifically either the cooling or the heating calibration signature.

Step 7. Alter the identified input parameter and rerun the simulation. The change should be made in the same direction as in the identified pair of characteristic signatures (e.g. increase or decrease). The amount of change should be estimated by comparing the magnitudes of the cooling and heating calibration signatures with the magnitudes of the cooling and heating characteristic signatures. Different values may be tested and the value with optimum results can be selected.

Step 8. Evaluate the new RMSE, residuals and cooling and heating calibration signatures. If the results of the calibration are not satisfactory, repeat from step 6 and iterate until the RMSE is minimal, the residuals are randomly scattered around zero and the calibration signature is flat and shows no trend with temperature.

Step 9. If daily data was used for the calibration, fine-tune the calibration by calibrating the simulation of hourly data. This can be achieved by introducing a daily load profile describing load variation during HVAC operating hours.

7. Applications of the Calibration Signature Method and Precautions

This approach to calibrated simulation has been used by the Energy Systems Laboratory (ESL) for several years in different applications. It has been used for diagnostics and prediction of the savings to be expected from commissioning projects. Table 1 compares calibrated simulation values of three system temperatures with site measured values and EMCS set points (Liu et al. 2002). The calibrated simulation predicted savings of $191,000 from commissioning this building with measured savings of $200,000. The process is fast enough that that it has been used to predict savings from commissioning measures in dozens of buildings in a variety of contracted commissioning jobs. Some of this work is described in Liu and Claridge (1995, 1998) and in Turner et al. (2003).

Table 1. Comparison of calibrated values of simulation parameters with site measured values and EMCS set points.

	Pre-cooling deck	Cold deck	Hot deck
"Calibrated" Value	52.0°F	52.0°F	85.0°F
Site Measured	52.8°F	51.5°F	85.0°F
EMCS Set Point	60.0°F	55.0°F	80.0°F

Calibrated simulation was used in five buildings in a study on the persistence of savings from commissioning. In this study, component failures in one building prevented accurate calibration, but in the remaining four buildings, consumption changes over a two year period were shown to closely agree with changes due to documented control changes in the buildings. (Turner et al., 2002, Claridge et al. 2002, Cho, 2002)

Calibrated simulation requires relatively detailed information about the building. It is advisable to check the calibrated values against values measured in the building when possible, particularly if the calibrated values differ significantly from the expected values. A calibrated simulation cannot accurately represent a building if the simulation is not capable of modeling an important phenomenon affecting the operation of the building. Factors such as duct leakage, terminal box leakage, and valve leakage are commonplace in buildings but are not commonly modeled by simulation programs.

The level of effort expended on calibration may be influenced by the intended use of the simulation. If the simulation will be used to project the impact of specific operational changes in a building, emphasis should be placed on accurately modeling the portions of the system that will undergo changes.

III. EXAMPLES OF USE OF CHARACTERISTIC SIGNATURES

Two examples are presented to illustrate the application of the calibration process described in section II.6. The first example illustrates the basic calibration steps using the signatures. The second is a more complex example in which more judgment must be used to perform the calibration. Both examples are based on a simulated building (i.e., the "measured" data used for the calibration is actually output from a simulation). The case studies presented in section IV show the use of this method with data from real buildings.

The two examples that follow use the building and DDCV system described in Appendix B. They were simulated using AirModel and Pasadena weather data.

1. Simple Example

Step 1. The results of an "accurate" or "baseline" simulation were used in this example as the "measured" data. Then, a set of "errors" was introduced into the simulation inputs to represent an uncalibrated simulation. The example illustrates the use of characteristic signatures to identify what these errors were. Pasadena weather data will be used.

Step 2. The uncalibrated simulation was conducted with hourly data.

Step 3. Hourly weather and cooling and heating data were converted to daily averages.

Step 4. The residuals, the RMSE and the calibration signatures were calculated for the initial simulation. The RMSE was found to be 0.05 MMBtu/hr and 0.07 MMBtu/hr respectively for cooling and heating energy consumption.

Step 5. Measured data (Meas), simulation results (Sim), residuals (Res) and calibration signatures (Sign) were plotted versus outside air dry-bulb temperature (T_{db}), as shown in Figure 5, for cooling (left) and heating (right). The signature magnitudes are shown on the right hand side y-axis. Note that the symbols for the simulated and measured results overlap, so they cannot be readily distinguished over much of the range.

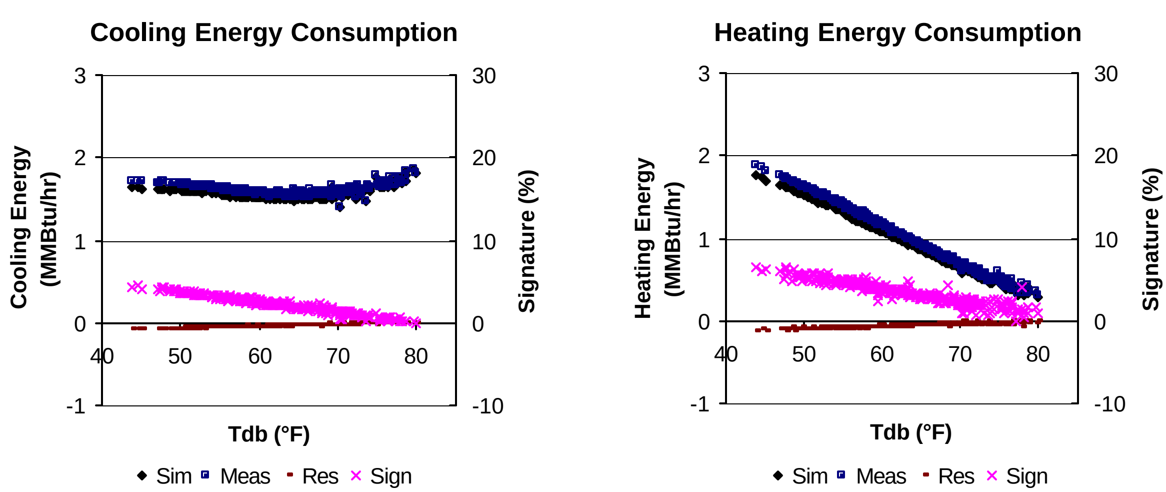


Figure 5. Initial simulation for Example 1 including calibration signatures

Step 6. The calibration signatures in Figure 5 should be compared to the characteristic signatures in Appendix E-1 corresponding to DDCV systems in Pasadena. We notice that the calibration signatures have positive values and negative slopes. They start at about 4% and 7% at low temperatures respectively for cooling and heating energy consumption, and approach zero at higher temperatures. We notice that they are comparable to the characteristic signatures of cold deck temperature, supply air flow rate and floor area for the characteristic signatures of Appendix E-1. Floor area was excluded because the cooling energy signature does not approach zero at high temperatures. In a real building simulation, site measurements of cold deck temperature and supply air flow may be used to determine which was not simulated accurately in the initial simulation. In this illustrative example, it was decided to change the cold deck temperature.

Step 7. In the characteristic signature of Appendix E-1, the cold deck temperature was decreased by 2 °F, which caused an increase of about 7% at low temperatures for both cooling and heating. Since the increase is of about 4% and 7% respectively for the cooling and heating calibration signatures, the cold deck temperature should be decreased by about 1 to 2 °F. Different values between 53 °F and 54 °F were tested during the first iteration and the cooling and heating RMSE values were summed and a minimal value was sought. The best result was obtained by decreasing the cold deck temperature from 55 to 53.6 °F.

Step 8. After this change, the RMS errors have both dropped considerably to 0.020 MMBtu/hr and 0.016 MMBtu/hr respectively for cooling and heating energy consumption. Figure 6 shows simulation charts after this first iteration.

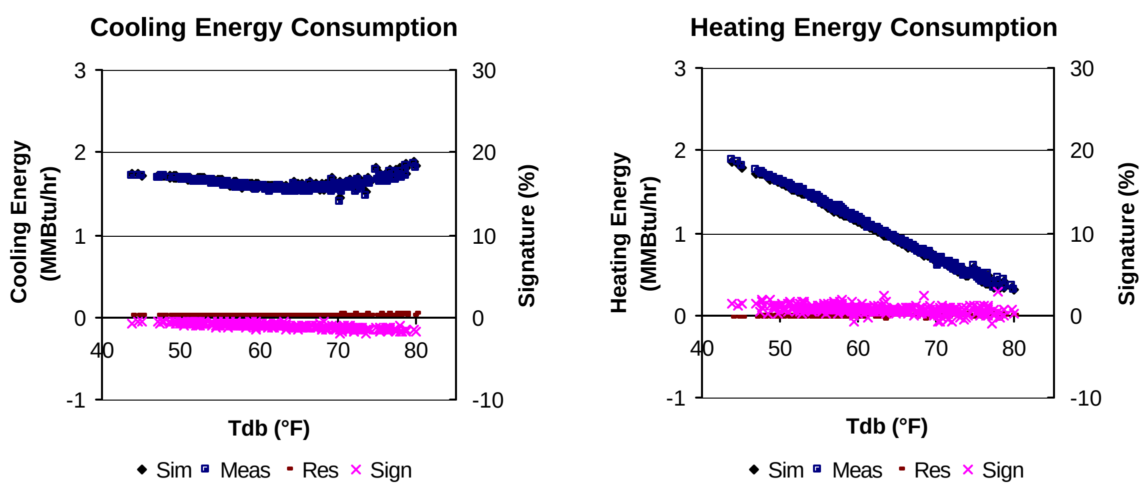


Figure 6. Simulation charts for Example 1 after the first iteration

The choice of the above mentioned value of the cold deck temperature was aimed to optimize both RMS errors for cooling and heating energy consumption. A higher value of 53.8 °F gave RMS errors of 0.013 and 0.024 MMBtu/hr, and a lower value of 53.4 °F gave RMS errors of 0.028 and 0.010 MMBtu/hr, respectively for cooling and heating energy consumption. The results of these simulations are shown in Figures 7 and 8.

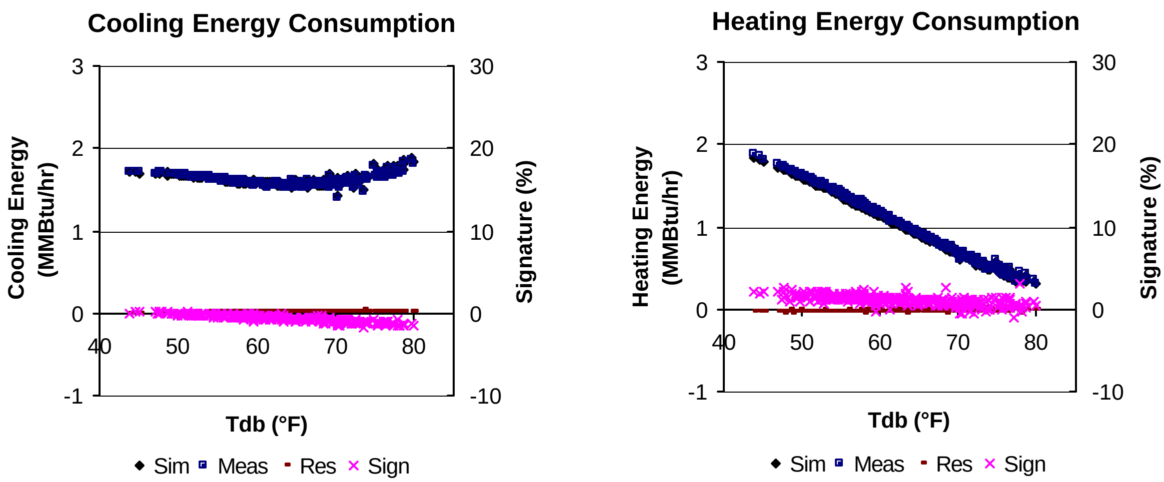


Figure 7. Simulation charts for Example 1 during first iteration with T_C = 53.8 °F

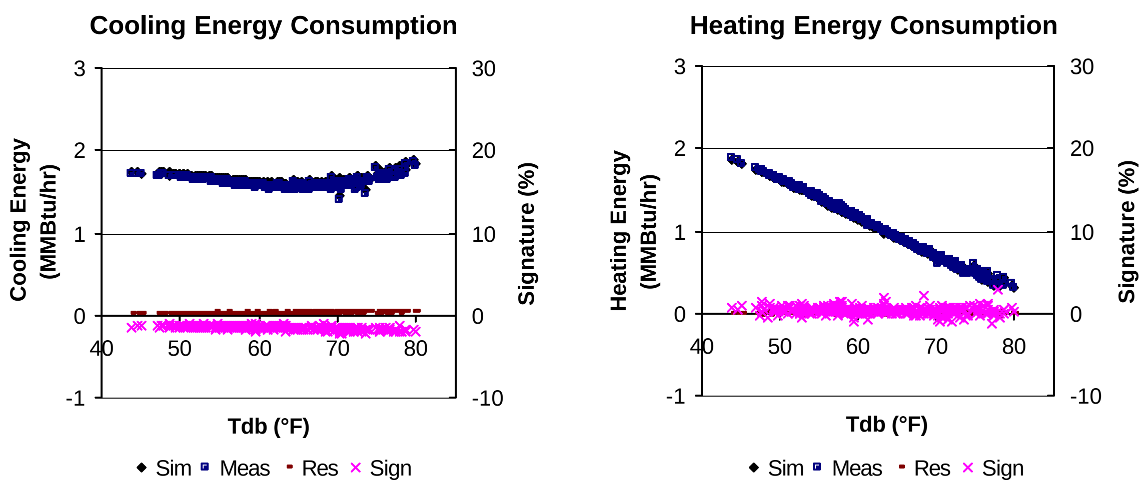


Figure 8. Simulation charts for Example 1 during first iteration with T_C = 53.4 °F

After the first iteration of the calibration process, the calibration signatures show improvement, but there are still significant errors, and the shape of the calibration signatures still show a detectable trend.

Iteration 2. The calibration signatures in Figure 6 have negative values for cooling and positive values for heating. They have negative slopes and approach zero at low temperatures for cooling, and at high temperatures for heating. Referring again to Appendix E-1, we notice that the characteristic signatures for decreasing the internal gain have the same characteristics. In the characteristic signature, a decrease of 0.4 W/ft^2 in internal gains caused maximum changes of about -9% and 7% respectively in cooling and heating energy use. The magnitude of the calibration signatures in Figure 6 reaches about –2% and 2% respectively for cooling and heating energy use, so internal gains should be decreased by about 0.1 W/ft^2. Different values between 0.65 and 0.85 W/ft^2 were tested and the best result was obtained by decreasing internal gains from 0.8 to 0.72 W/ft^2.

After this iteration, the calibration signatures and RMS errors dropped to zero. Figure 9 shows calibrated simulation charts.

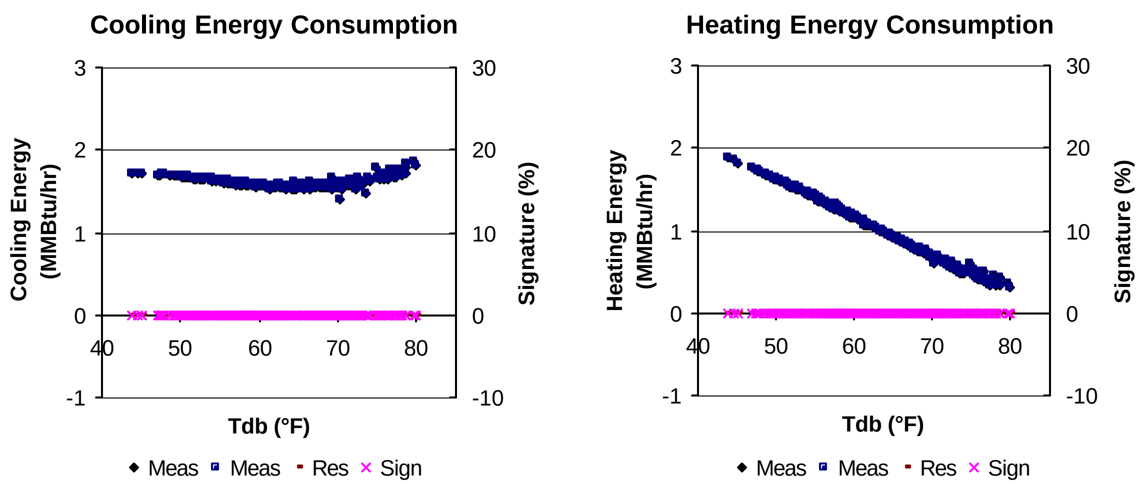


Figure 9. Calibrated simulation for Example 1

2. More complex example

This example utilizes the same building, system used in the previous example and described in Appendix B. In this example, a more complex set of differences were introduced into the "uncalibrated" simulation to increase the difficulty of the calibration process. In addition, the person who devised the baseline simulation that produced the synthetic "measured" data was not the same individual who conducted the calibration. It was therefore possible at the end of the process to compare the final inputs that were selected through the calibration process with the "real" inputs that had been used, and to comment on how successfully the simulation was calibrated.

Step 1. The results of a "baseline" simulation were used in this example as the "measured" data. Then, the individual who conducted the calibration was given a different set of inputs as the inputs for the "uncalibrated" simulation. The example illustrates the use of characteristic signatures to identify the changes needed to calibrate the simulation. Pasadena weather data was used.

Step 2. The uncalibrated simulation was conducted with hourly data.

Step 3. Hourly weather and cooling and heating data were converted to daily averages.

Step 4. The residuals, the RMSE and the calibration signatures were calculated for the initial simulation. The RMSE was found to be 0.07 MMBtu/hr and 0.18 MMBtu/hr respectively for cooling and heating energy consumption.

Step 5. Measured data (Meas), simulation results (Sim), residuals (Res) and calibration signatures (Sign) were plotted versus outside air dry-bulb temperature (T_{db}), as shown in figure 10, for cooling (left) and heating (right). Signature magnitudes are shown on the right hand side y-axis.

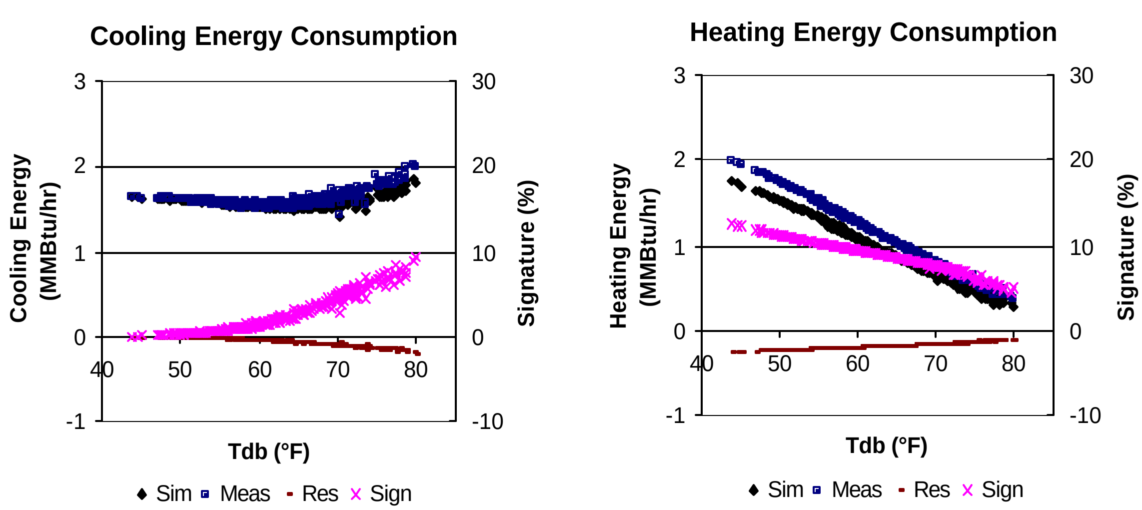


Figure 10. Initial simulation for Example 2 including calibration signatures

Step 6. We examine the calibration signatures of the first simulation as shown in Figure 10. We note that the cooling signature is almost 10% at high temperatures, but close to zero at low temperatures. While the heating signature always has significant positive values, it has the opposite slope. Examining the characteristic signatures in Appendix E-1, we see that only outside air and envelope U-value have this combination of opposite slopes. Neither has a strong positive value throughout the range of outside temperatures, so we assume the calibration signatures represent a combination of multiple characteristic signatures. We choose to modify the outside air quantity, since both calibration signatures reach large values at extreme temperatures, more like those of the outside air signatures than the envelope U-values.

Step 7. In the characteristic signature of Appendix E-1, the outside air flow rate was increased by 0.05 cfm/ft^2, which caused an increase of about 15% in cooling and a decrease of about 8% in heating across the entire range of ambient temperature. In the calibration signatures the change was about 10% and -8% respectively for cooling and heating. This suggests that the outside air flow rate should be increased by about 0.05 cfm/ft^2 or less. Different increments ranging from 0.02 to 0.06 cfm were tested and the best result was obtained by increasing the outside air flow rate from 0.10 to 0.14 cfm/ft^2.

Step 8. After this change, the calibration signature approached zero at high temperatures for cooling, but increased at low temperatures. The cooling RMSE remained at 0.07 MMBtu/hr, but the signature became more uniform across the entire temperature range. For heating, the signature is noticeably smaller at low temperatures, but has changed little at high temperatures. The heating RMSE decreased from 0.18 to 0.16 MMBtu/hr. Figure 11 shows simulation charts after this first iteration.

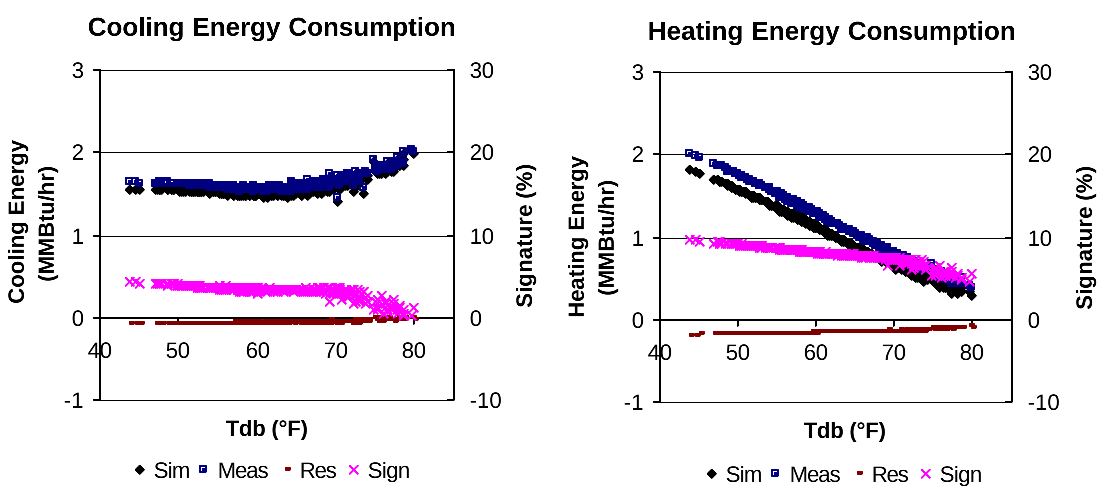


Figure 11. Simulation charts for Example 2 after the first iteration

Iteration 2. We see that we need to alter a calibration parameter so that both cooling and heating energy consumption increase over the entire range of outside air temperature, and the characteristic signatures for both cooling and heating should have negative slopes. Examining the characteristic signatures of Appendix E-1, we see that decreasing the cold deck temperature, increasing the supply air, or increasing the floor area all have these general characteristics. We note that increasing the floor area had a fairly large cooling characteristic signature at high temperatures, while the cooling calibration signature of Figure 11 is near zero at high temperatures, so we consider only cold deck temperature or supply air flow rate at this point. This is often true - the calibration signatures will not suggest a single option, but will point toward a small number of options. It is relatively easy to measure cold deck temperatures, so that would be a logical step at this point if one has access to the building. In this illustrative example, we chose to decrease the cold deck temperature because its cooling characteristic signature reaches zero at high temperatures.

It was not possible to bring both cooling and heating calibration signatures to zero by decreasing the cold deck temperature, but we found that when the cold deck temperature was decreased from 55 to 54 °F, the cooling RMSE dropped considerably from 0.07 to 0.02 MMBtu/hr. Both cooling and heating calibration signatures dropped over almost the entire range of outdoor temperatures as shown in Figure 12. The heating RMSE decreased from 0.16 to 0.12 MMBtu/h.

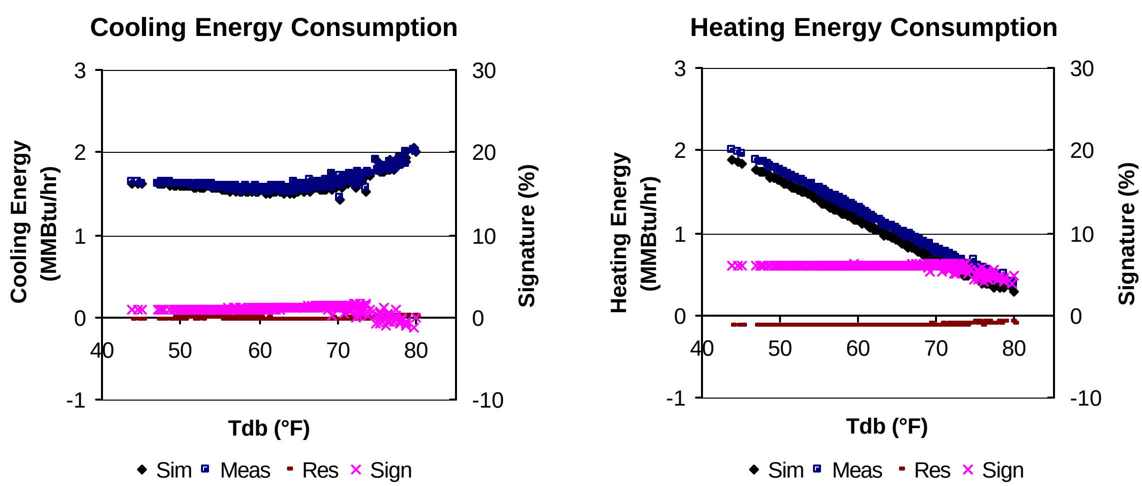


Figure 12. Simulation charts for Example 2 after iteration 2

Iteration 3. The calibration signatures are now both positive, but the heating signature is considerably larger than the cooling signature. None of the characteristic signatures match these characteristics, but room temperature characteristic signatures are both positive at low temperatures and the heating characteristic signature is twice as large as that of cooling. This calibration step will target the low temperature range assuming that the calibration signatures of Figure 12 require a set of combined characteristic signatures. In the characteristic signature, increasing the room temperature from 73 °F to 74 °F caused energy use to increase by 2% and 4% at low temperatures respectively for cooling and heating, while the calibration signatures are at 1% and 6% at low temperatures respectively for cooling and heating. This suggests that increasing room temperature by about 0.5 °F should bring the cooling calibration signature to zero at low temperatures, and increasing it by 1.5 °F should bring the heating calibration signature to zero at low temperature. It was decided to increase room temperature by only 0.5 °F to avoid too much effect on the high temperature side. The room temperature setpoint was therefore increased from 73 °F to 73.5 °F. Figure 13 shows simulation charts after this change. As expected, the cooling calibration signature has approached zero at low temperatures, but the cooling RMSE has actually increased slightly from 0.02 to 0.03 MMBtu/hr due to the slight increase at high temperatures. The heating RMSE has decreased slightly from 0.12 to 0.11 MMBtu/hr.

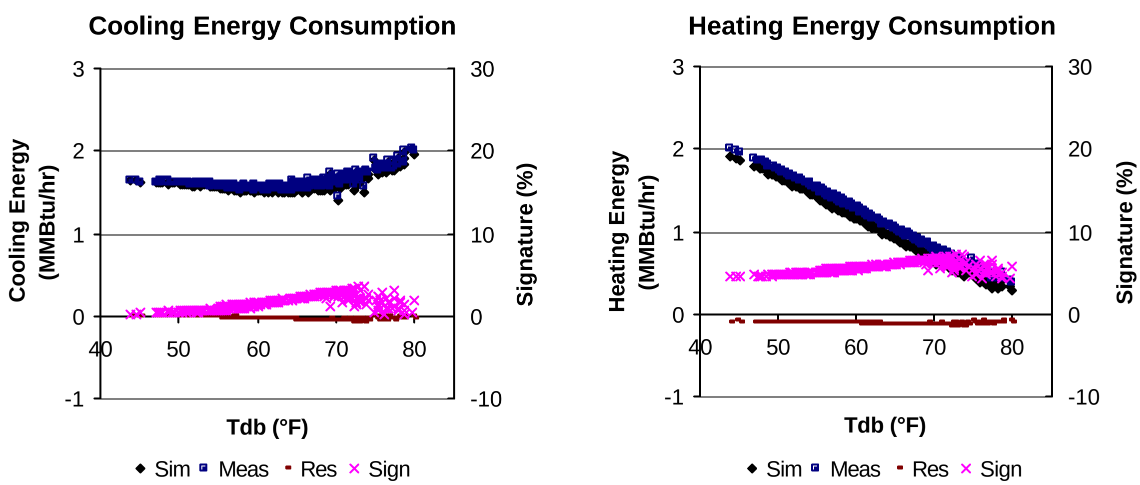


Figure 13. Simulation charts for Example 2 after iteration 3

Iteration 4. We now have peaks in the middle range of high temperatures in both the cooling and heating calibration signatures. Examination of the characteristic signatures of Appendix E-1 indicates that the hot deck temperature characteristic signatures have a similar trend. We found out that increasing the hot deck temperature to remove the peaks caused the RMSE to decrease for heating and increase for cooling, so both RMSE values were summed and a minimum value was sought. The best result was obtained by increasing the hot deck temperature by 2 °F. The heating RMSE dropped sharply from 0.11 MMBtu/hr to 0.04 MMBtu/hr and the cooling RMSE increased slightly from 0.03 to 0.05 MMBtu/hr. After this alteration, the peaks have been removed as shown in Figure 14.

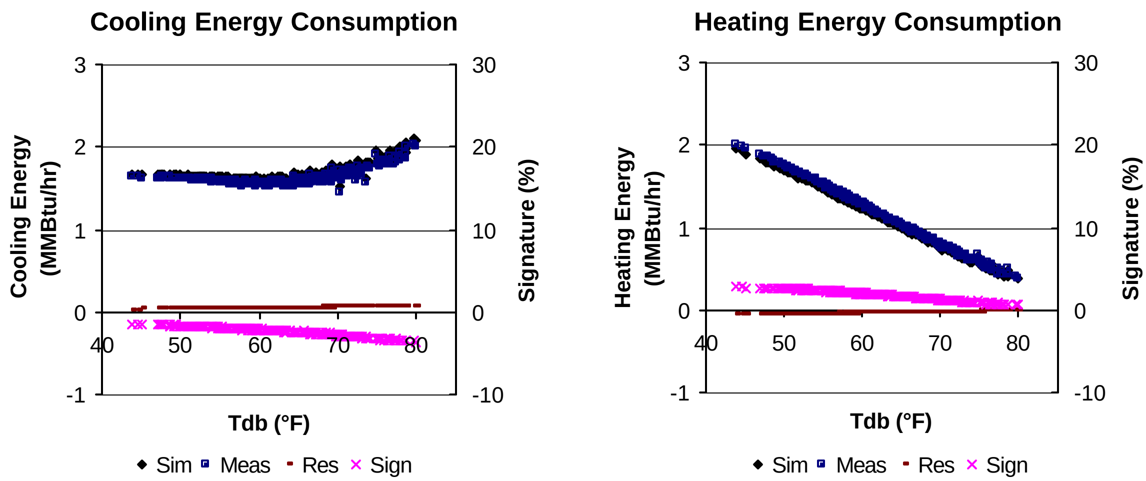


Figure 14. Simulation charts for Example 2 after iteration 4

Iteration 5. The calibration signature for cooling is now negative with a negative slope while the heating signature is positive with a negative slope. Alternatively, we can say that cooling energy consumption needs to be decreased, and heating energy consumption increased over the entire temperature range. The change should tend to zero at lower temperatures for cooling consumption, and at higher temperatures for heating consumption. Examining the signatures of Appendix E-1 shows that only a decrease in internal gain level has a similar set of signatures. In this set of signatures, a decrease of 0.4 W/ft^2 in internal gains caused maximum changes of -9% and 7% respectively for cooling and heating, while the calibration signatures reach -4% and 3% respectively for cooling and heating. This suggests that internal gains have to be decreased by about 0.15 to 0.2 W/ft^2. Different values were tested and the best result was obtained by decreasing internal gains from so 0.8 to 0.6 W/ft^2. It provided an extremely good match as shown in Figure 15. The calibration signatures have dropped to near zero over the whole range of temperatures, and the RMS errors are only 0.003 and 0.001 MMBtu/hr respectively for cooling and heating energy consumption. The simulation model is now calibrated.

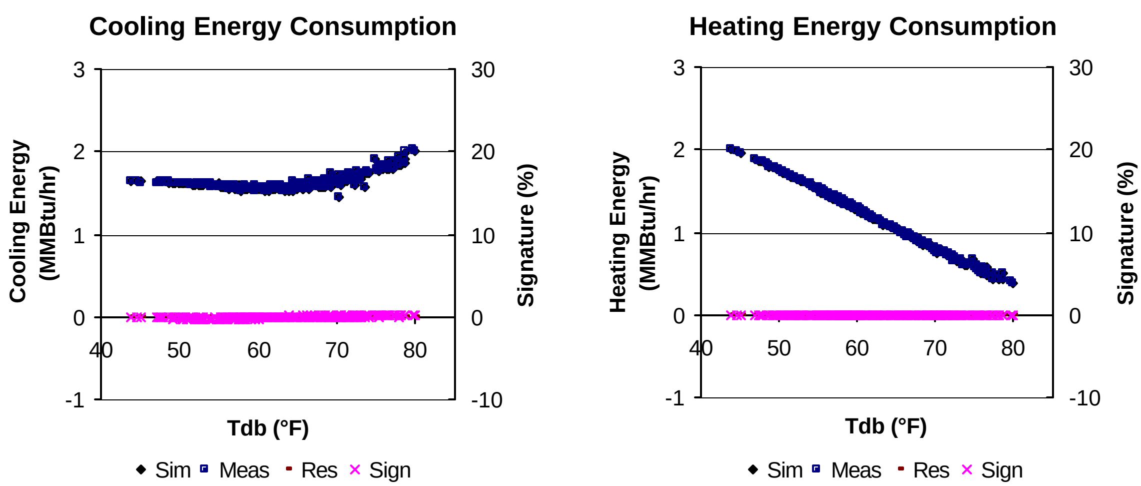


Figure 15. Calibrated simulation for Example 2

In this example, the generation of the original simulation the provided the "measured" data and the calibration process were conducted by two people. This was done to provide more realistic calibration conditions where the answer was not known by the one performing the calibration. The alterations made to generate the uncalibrated simulation and those made to calibrate the system are compared in Table 2.

Table 2. Comparison of calibration alterations with "real" errors

Input parameter	Model calibration	"Measured" Value
Outside air flow rate	0.1 → 0.14 cfm/ft^2	0.14 cfm/ft^2
Cold deck Temperature	55 → 54 °F	53.6 °F
Room Temperature	73 → 73.5 °F	73 °F
Hot deck Temperature	110 → 112 °F at T_{OA}=40 °F 80 → 82 °F at T_{OA}=70 °F 70 → 72 °F at T_{OA}=100 °F	111.5 °F at T_{OA}=40 °F 81.5 °F at T_{OA}=70 °F 71.5 °F at T_{OA}=100 °F
Internal heat gain	0.8 → 0.6 W/ft^2	0.55 W/ft^2

We notice that the changes made to input parameters to calibrate the model are close to those needed to correct the errors that were intentionally introduced to simulate the real building. Temperature differences were 0.5 °F or less, which is comparable to measurement accuracy.

Note that step 9 (hourly fine tuning) of the calibration procedure was not used in these examples. This step is rather helpful when calibrating to real data, which typically produces somewhat more scatter in the results than shown in these examples that used "measured" data generated by a simulation program. The case studies presented in the next section show the use of this final calibration step in real buildings.

IV. CASE STUDIES

This section describes two additional examples, using data from real buildings rather than simulations. These examples show that in real buildings, issues such as lack of sufficient measured data, operational changes, complex occupancy schedules, and multiplicity of systems can make the calibration process somewhat more complicated, but that the characteristic calibration signatures method still allowed the analyst to define a believable simulation with minimal effort.

The first building is located in Oakland, CA and the second in College Station, TX. In the second example, characteristic signatures were built using the building's own simulation since the published generic signatures in this manual correspond to a different climate. Appendix G shows how to create one's own characteristic signatures.

1. Case Study 1: Dalziel Building, Oakland, CA.

The Oakland Administration Building was constructed in 1998. It consists of two separate buildings, the Dalziel Building and the Wilson Building, with a combined gross area of 450,000 ft^2 and a relatively low whole building energy use of 50 $kBtu/ft^2/yr$ (Motegi et al, 2002).

The objective of this case study was to calibrate the simulation of cooling and heating energy consumption for Dalziel. This building, shown in Figure 16, has six floors with an estimated conditioned floor area of about 230,000 ft^2. The main HVAC system is a Single Duct Variable Air Volume (SDVAV) system with hot water reheat. Two 500-ton chillers, located in Dalziel, serve the main air handlers in both buildings, while each building has its own hot water boilers.

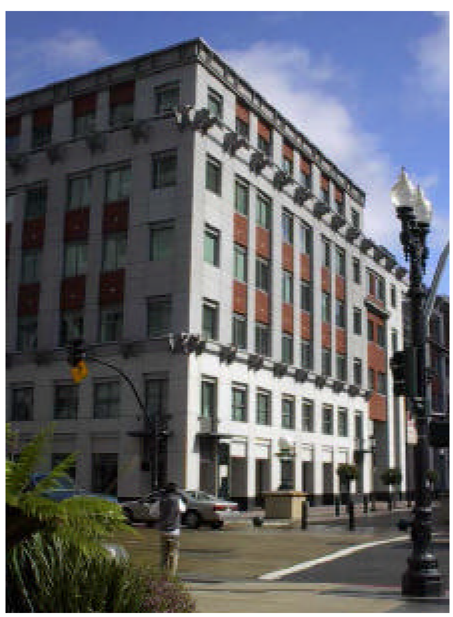


Figure 16. Picture of the Dalziel Building

Step 1. The major difficulty encountered in calibrating the Dalziel Building was frequent changes in the operating schedule of the building systems. In the interest of avoiding this issue, this case study considers only a 3-month period when the schedule was consistent, i.e. March 5 to June 2, 2000.

Step 2. AirModel was used for the simulation. The main input parameters for the initial simulation are shown in Table 3. They were taken or calculated from a report on the Oakland Administration Building (Eley Associates, 2001), as well as a set of files that includes measured data and input and output files from an earlier DOE-2 simulation provided by Motegi (Motegi, 2002). These input parameters were considered to be representative of expected operation of the building. Monthly solar gains were calculated using the Klein-Theilacker method (Duffie and Beckman, 1991). The months of December and July were established as having respectively the minimum and maximum solar gains. These two months were therefore used as the maximum and minimum solar gain inputs as required by AirModel as shown in Table 3. AirModel approximates solar gains as a linear function of outside air temperature (Knebel, 1983).

Table 3. Initial simulation parameters for case study 1

Parameter	**Value**
Conditioned floor area	231,557 ft^2
Interior zone ratio	0.2
Occupied period	6 am to 6 pm on weekdays only
Exterior wall and roof area	91.982 ft^2
Average exterior wall and roof U-value	0.073 Btu/ft^2.hr.°F
Window area	19,339 ft^2
Window U-value	0.34 Btu/ft^2.hr.°F
Room temperature setpoint T_{room}	72 °F
Minimum air flow rate	0.34 cfm/ft^2
Outside air flow rate	0.28 cfm/ft^2
Economizer range	40 - 70 °F
Average internal heat gain Q_{int}	1.8 W/ft^2
Solar gains	0.078 MMBtu/h at 42 °F, and 0.138 MMBtu/h at 88 °F
Air infiltration	None
Average occupancy	356 ft^2/person
Difference between return and room air temperatures	2 °F
Cold deck temperature T_c	64 °F
Preheat location	Outside air
Preheat temperature T_{ph} schedule	45 °F for T_{OA}<45 °F

Site measured weather data was used for the simulation. Figure 17 shows daily average dry-bulb temperature variations over the simulation period, and daily average relative humidity versus daily average dry-bulb temperature.

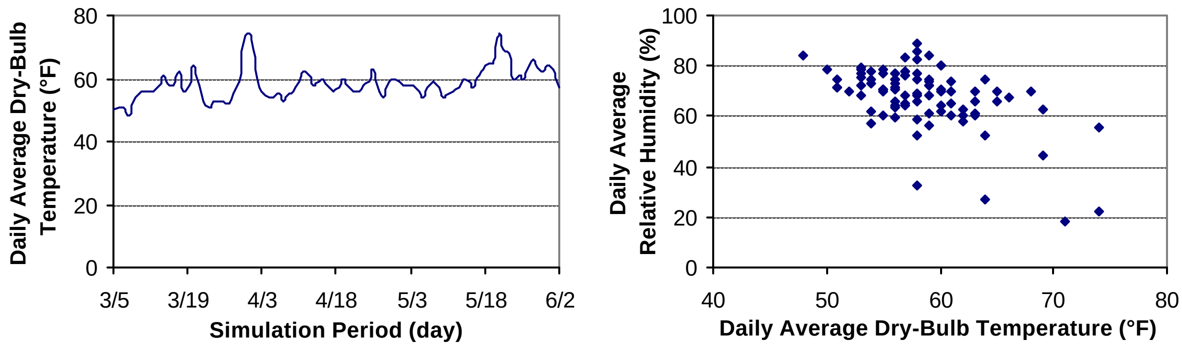


Figure 17. Weather conditions for the simulation period

Step 3. Daily average values were used for this simulation. In the authors' experience, using daily averages helps eliminate dynamic effects and reduce the scatter. The major difficulty was the small number of cooling data points. The number of hourly cooling data points was very small because chillers were turned off whenever the ambient temperature was less than 65°F; a large number of hourly measurements were also missing, so a number of days with insufficient hourly data were eliminated. In the absence of reliable cooling data, a model was created for cooling energy consumption using measured data from the period between June 5 and August 7, 2001, for which considerably more daily average cooling energy consumption (Q_{cool}) data points could be generated. The 3-parameter change point linear regression model of cooling consumption generated from this data was:

$$
\begin{array}{lll}
Q_{cool}\ (\text{MMBtu/hr}) & = 0 & \text{for } T_{db}\ (°\text{F}) < 59.63\ °\text{F} \\
 & = 0.0737\ T_{db}\ (°\text{F}) - 4.3949 & \text{for } T_{db}\ (°\text{F}) \geq 59.63\ °\text{F}
\end{array}
$$

Step 4. The RMS errors for the initial simulation were 0.13 and 0.36 MMBtu/hr respectively for cooling and heating energy consumption.

Step 5. Cooling and heating simulation charts for all calibration steps are illustrated in Figures 18 to 24 and in Figure 29. Figure 18 shows the initial simulation and Figure 29 shows the calibrated simulation. Each of these figures consists of four charts. The two charts on the left hand side are cooling charts and the two charts on the right hand side are heating charts. The upper ones show simulated (sim) and measured (meas) daily average energy consumption, as well as residuals (res) as defined in equation 2. The lower graphs show calibration signatures as defined in equation 1. The purpose of the solid line in the calibration signatures is to reveal the trend of the scattered data points, which makes it easier to compare the calibration signature to characteristic signatures. The trend line is a moving average of 6 points for cooling and 9 points for heating. Groups of an equal number of points have been used rather than temperature bins because data points were not distributed uniformly over the temperature range, and more points were used per group for heating than for cooling because there were considerably more heating than cooling data points.

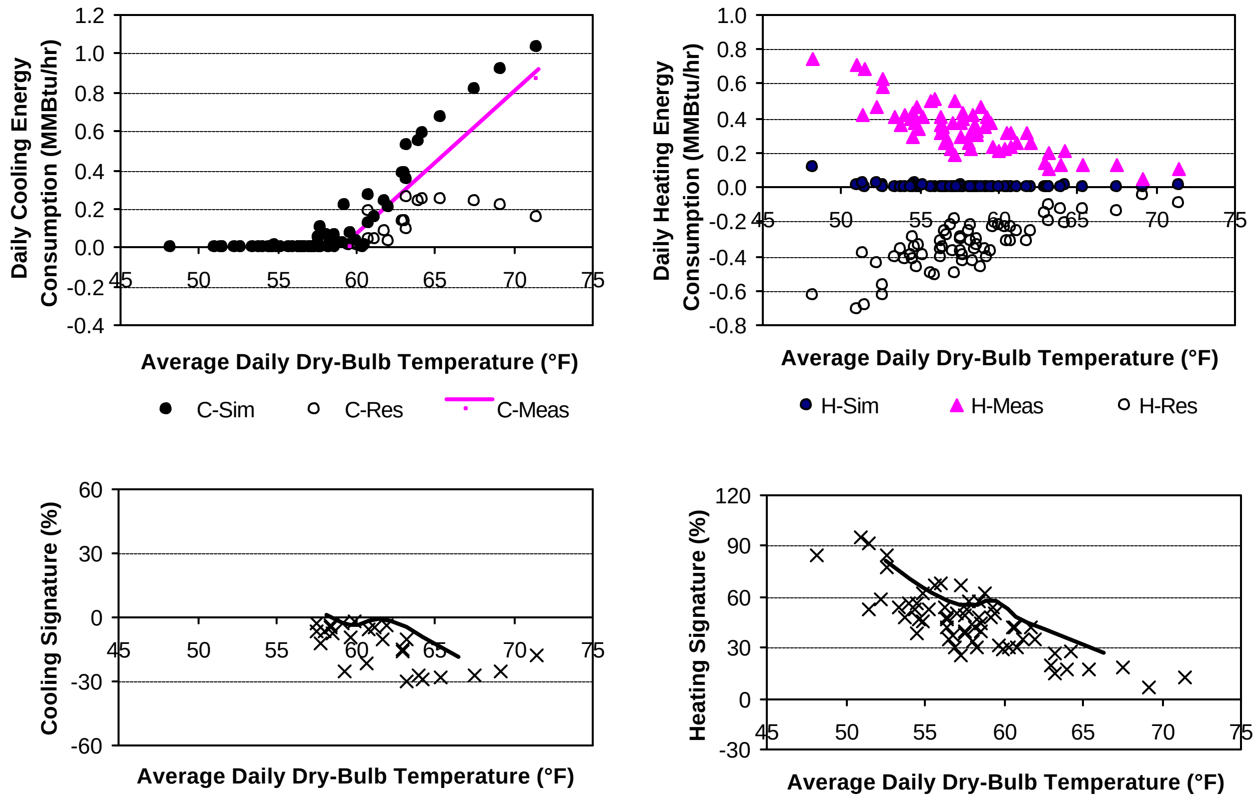


Figure 18. Initial simulation charts for case study 1

Step 6. After running the initial simulation, the major remark is that heating energy consumption is simulated to be zero, while the cooling simulation signature is relatively small. The objective of the first input change should be to produce heating energy consumption over the entire temperature range. The characteristic signatures in Appendix D-3, corresponding to SDVAV systems in Oakland, will be used for this case study. Examining these characteristic signatures, we notice that decreasing the cold deck temperature, increasing the minimum air flow rate, increasing the floor area, decreasing internal gains or increasing room temperature would cause heating to increase uniformly over the entire temperature range. Since the objective of this input change is to increase heating consumption as much as possible, the parameter to be altered for Iteration 1 will be chosen as the most sensitive among those mentioned above. The minimum air flow rate seems to be the most sensitive, since a decrease of as little as 0.03 cfm/ft^2 caused heating energy use to decrease by about 6% over the entire temperature range.

Step 7. The minimum air flow rate characteristic signature for heating is negative, while the heating calibration signature is positive, so the input parameter should be altered in the opposite sense, i.e. increased. The minimum air flow rate was increased to 0.8 cfm/ft^2.

Step 8. Figure 19 shows simulation charts after this change. The heating RMSE has decreased considerably from 0.36 to 0.28 MMBtu/hr. We notice that the effect of increasing the minimum air flow rate was more pronounced in the lower temperature range, while there was not much effect at higher temperatures, which explains why the cooling RMSE remained at 0.13 MMBtu/hr as there is no cooling energy consumption at low temperatures.

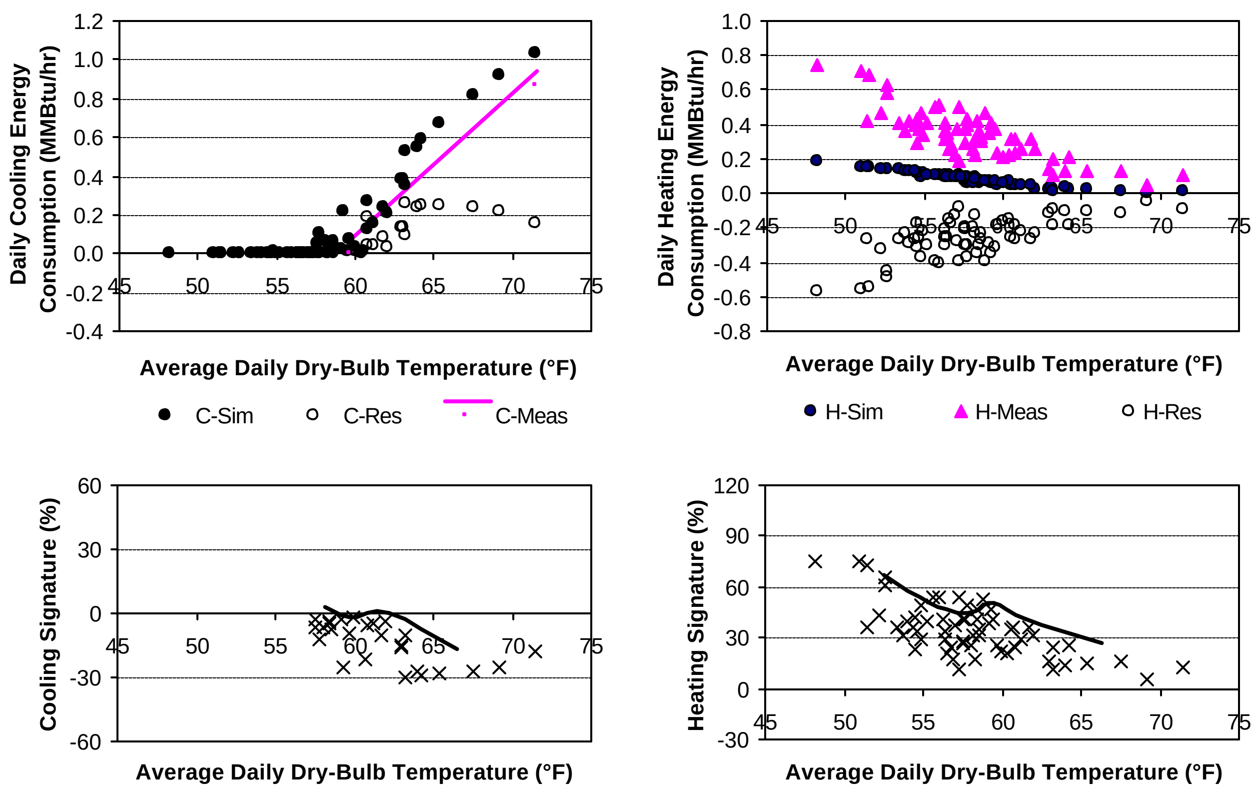


Figure 19. Cooling and heating simulation charts after the first iteration

Iteration 2. The calibration signature was considerably decreased for heating in Iteration 1. However, it still remains as large as 75% at low temperatures, while the cooling simulation signature is within -30%. This calibration step will focus again on heating energy consumption. Examining the characteristic signatures in Appendix D-3, we notice that decreasing the internal gain should decrease the heating calibration signature over the total temperature range without much effect on cooling. It should even decrease the cooling calibration signature at high temperatures since the cooling characteristic signature also has a negative slope at high temperatures. The best result was obtained by decreasing the internal heat gain from 1.8 to 1.25 W/ft^2. Figure 20 shows simulation charts after this change. The RMS errors have decreased from 0.13 to 0.11 MMBtu/hr for cooling and from 0.28 to 0.12 MMBtu/hr for heating.

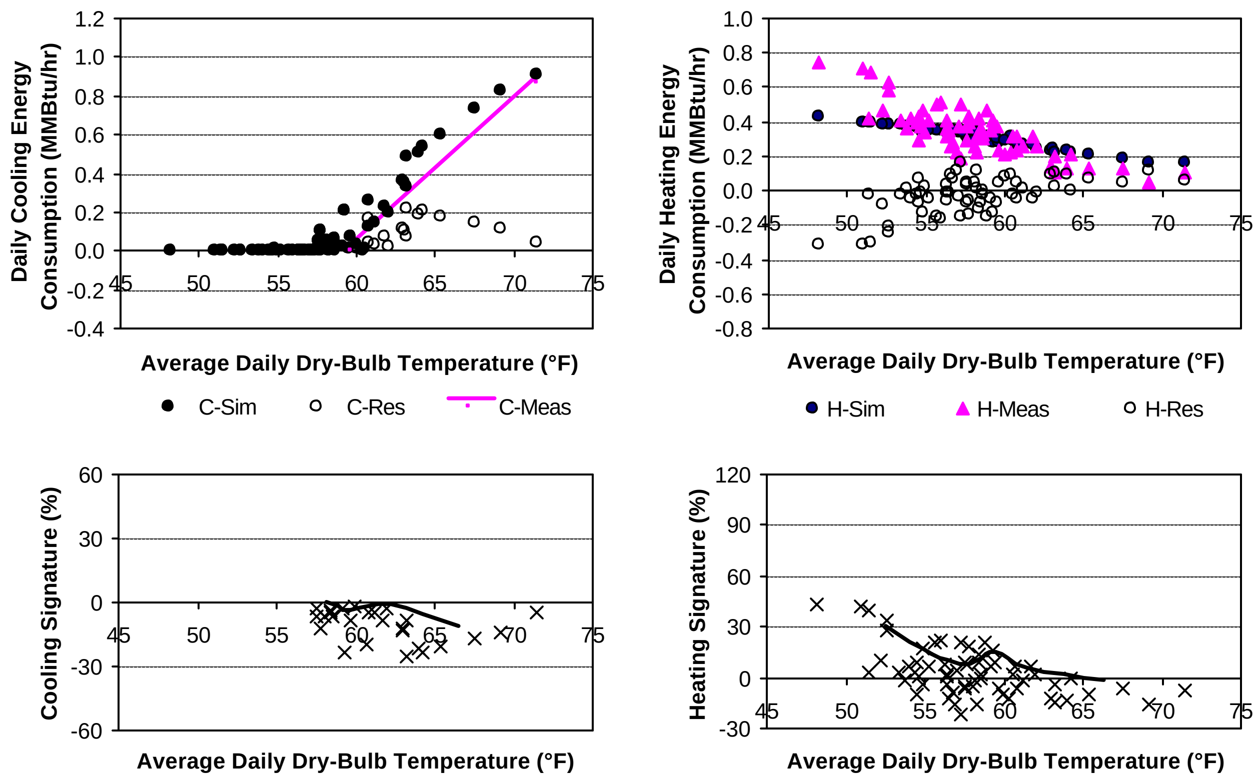


Figure 20. Cooling and heating simulation charts after iteration 2

Iteration 3. Both cooling and heating RMS errors have decreased after Iteration 2. But, the heating calibration signature still has a steep negative slope at low temperatures. Examining the characteristic signatures in Appendix D-3, we notice that the heating characteristic signature for outside air is comparable to the heating calibration signature in Figure 20. Therefore, increasing the outside air flow rate should neutralize or reduce the negative slope at low temperatures in the heating calibration signature. The calibration and characteristic signatures for cooling do not match. In order to reduce the effect on the cooling calibration signatures, the outside air flow rate was increased to partially neutralize the negative slope at low temperatures for heating and make it uniform with the rest of the signature. The outside air flow rate was increased from 0.28 to 0.42 cfm/ft^2. Figure 21 shows simulation charts after this alteration. The RMSE has decreased from 0.12 to 0.10 MMBtu/hr for heating and increased slightly from 0.11 to 0.12 MMBtu/hr for cooling.

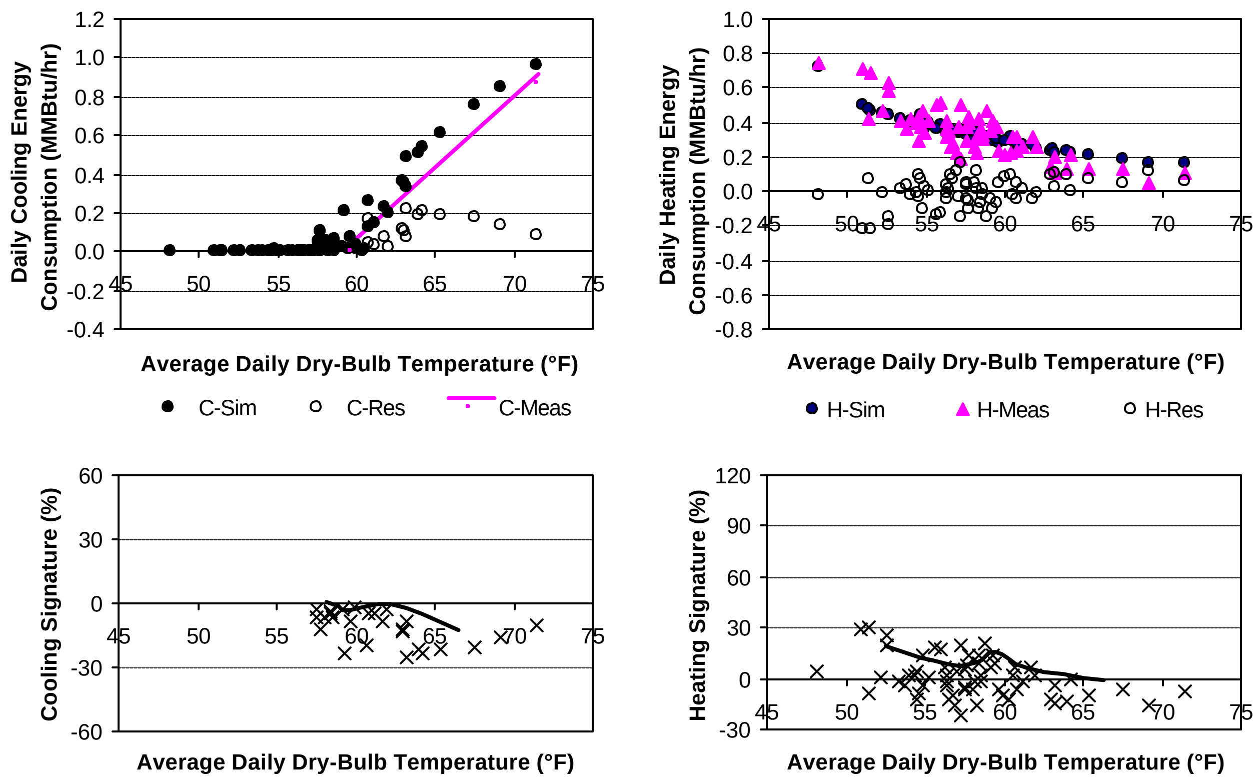


Figure 21. Cooling and heating simulation charts after iteration 3

Iteration 4. Now that the heating simulation signature has been reduced to reasonable values, the purpose of this calibration step is to reduce the cooling simulation signature over the entire temperature range. The cooling calibration signature in Figure 21 is negative over the total temperature range. It is almost constant at lower temperatures and has a negative slope at high temperatures. Examining the characteristic signatures in Appendix D-3, we notice that the cooling characteristic signatures for the cold deck temperature (T_c) and the room temperature setpoint (T_{room}) have similar trends and are both positive. Therefore, decreasing the cold deck temperature and/or increasing the room temperature setpoint should neutralize the negative slope at high temperatures, but would increase cooling energy consumption at lower temperatures instead of decreasing it. Similarly, increasing the cold deck temperature and/or decreasing the room temperature setpoint should decrease cooling energy consumption, but would make the negative slope at high temperatures even steeper. In order to decreasing cooling energy consumption and at the same time neutralize the negative slope at high temperatures, both the cold deck temperature and the room temperature setpoint have to be altered, one in the same direction as in the characteristic signature and one in the opposite direction, i.e. both increased or decreased. The best result was obtained by increasing the cold deck temperature from 64 °F to 66 °F and the room temperature setpoint from 72 °F to 73.5 °F. Figure 22 shows simulation charts after this iteration. The RMSE has decreased considerably for cooling from 0.12 to 0.06 MMBtu/hr. It has decreased slightly for heating from 0.10 to 0.09 MMBtu/hr.

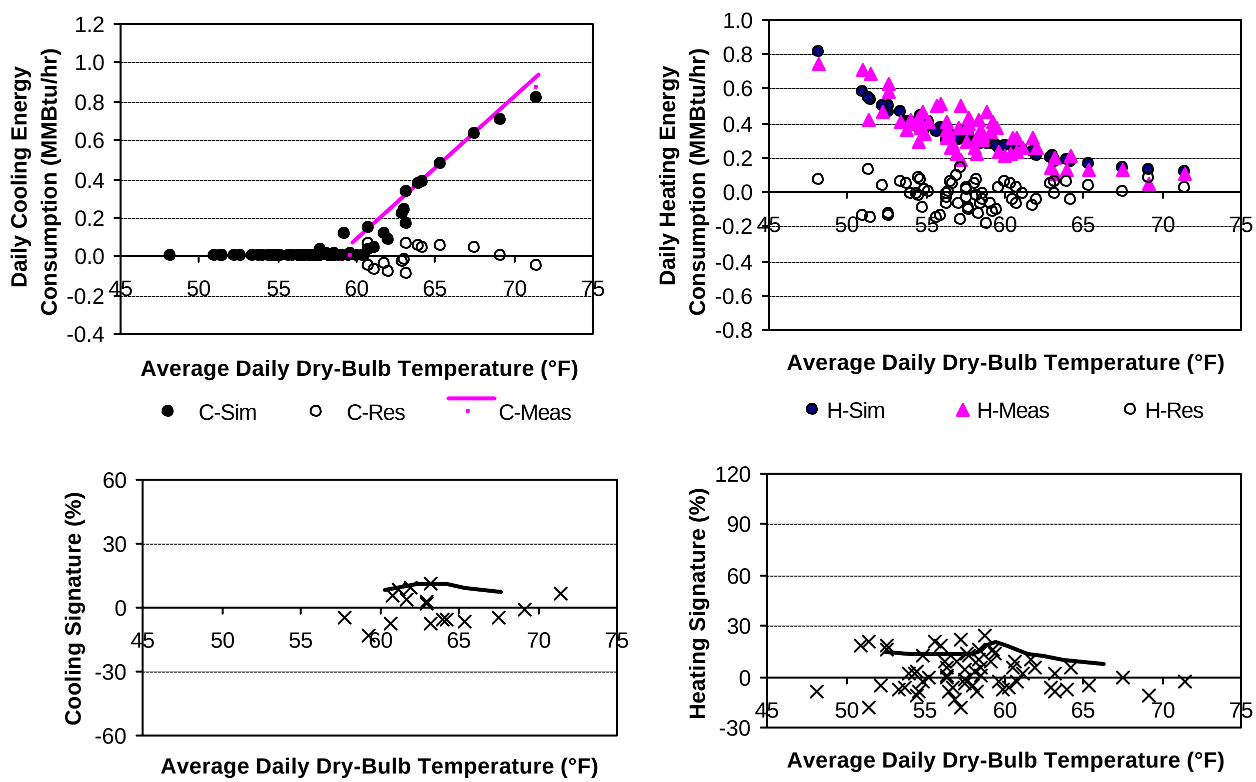


Figure 22. Cooling and heating simulation charts after iteration 4

Iteration 5. Both cooling and heating RMS errors have decreased to reasonable values in the previous simulation. But, we notice that the heating calibration signature in Figure 22 still has a slightly negative slope. Examining Appendix D-3, we notice that the heating characteristic signature for the envelope U-value has a constant positive slope. This characteristic signature was obtained by decreasing the envelope U-value. Therefore, the envelope U-value has to be increased in this calibration step to match the negative slope of the heating calibration signature. The best result was obtained by increasing the U-value by 20%. Consequently the exterior wall and window U-values were increased respectively from 0.073 to 0.088 Btu/ ft^2.hr.°F and from 0.34 to 0.41 Btu/ ft^2.hr.°F. Figure 23 shows simulation charts after this iteration. The RMSE has slightly decreased for heating from 0.09 to 0.08 MMBtu/hr and remained at 0.06 MMBtu/hr for cooling.

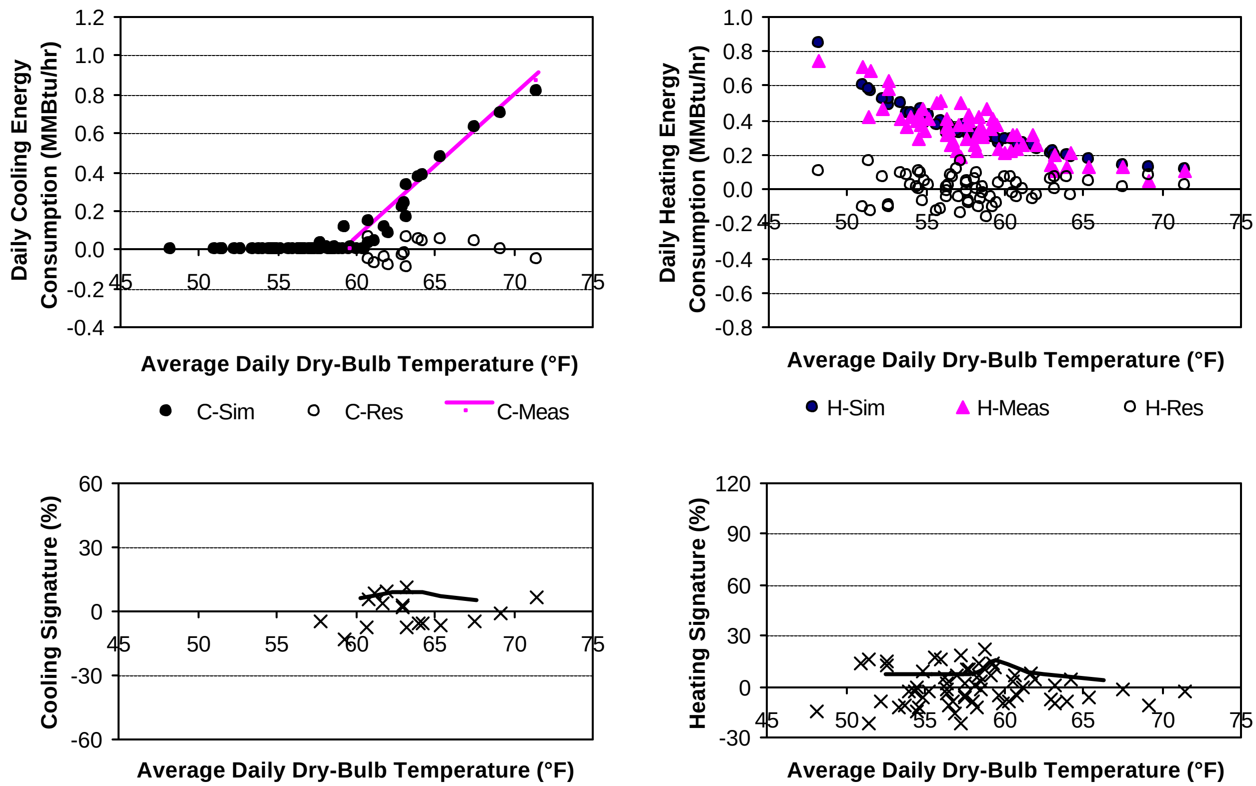


Figure 23. Cooling and heating simulation charts after iteration 5

Step 9. The objective is to fine-tune the calibration by calibrating the simulation of hourly data. This is achieved by introducing the daily internal gain profile, shown in the right hand side of figure 24, and calculated from the hourly variations of light and plug loads in the building, shown in the left hand side of figure 24. The daily internal gain profile was defined for each hour as the ratio of the internal gain to the maximum internal gain. It was calculated for weekdays only as there were no vacation periods and the HVAC system was shut off on weekends during the calibration period.

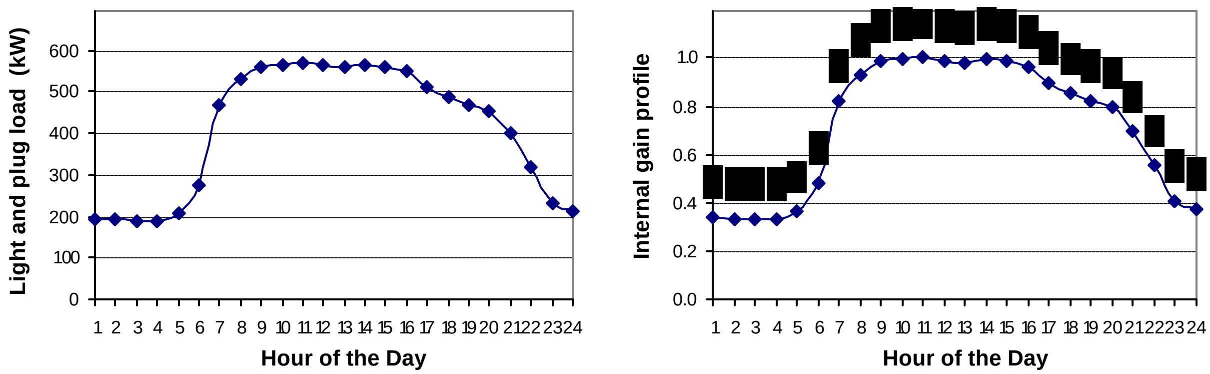


Figure 24. Hourly light & plug load (left) and deduced daily internal gain profile (right)

Therefore, instead of using an average heat gain of 1.25 W/ft^2 for each hour of the day, a maximum internal gain will be used along with the internal gain profile of figure 24. The only parameter that needs to be adjusted is the maximum internal gain. Different values were tested and the best result was obtained with 1.42 W/ft^2.

Figure 25 shows calibrated simulation charts. We notice on the heating calibration signature that the hourly calibration has reduced the negative slope at high temperatures. The heating RMSE has actually decreased from 0.08 to 0.07 MMBtu/hr while the cooling RMSE has remained at 0.06 MMBtu/hr.

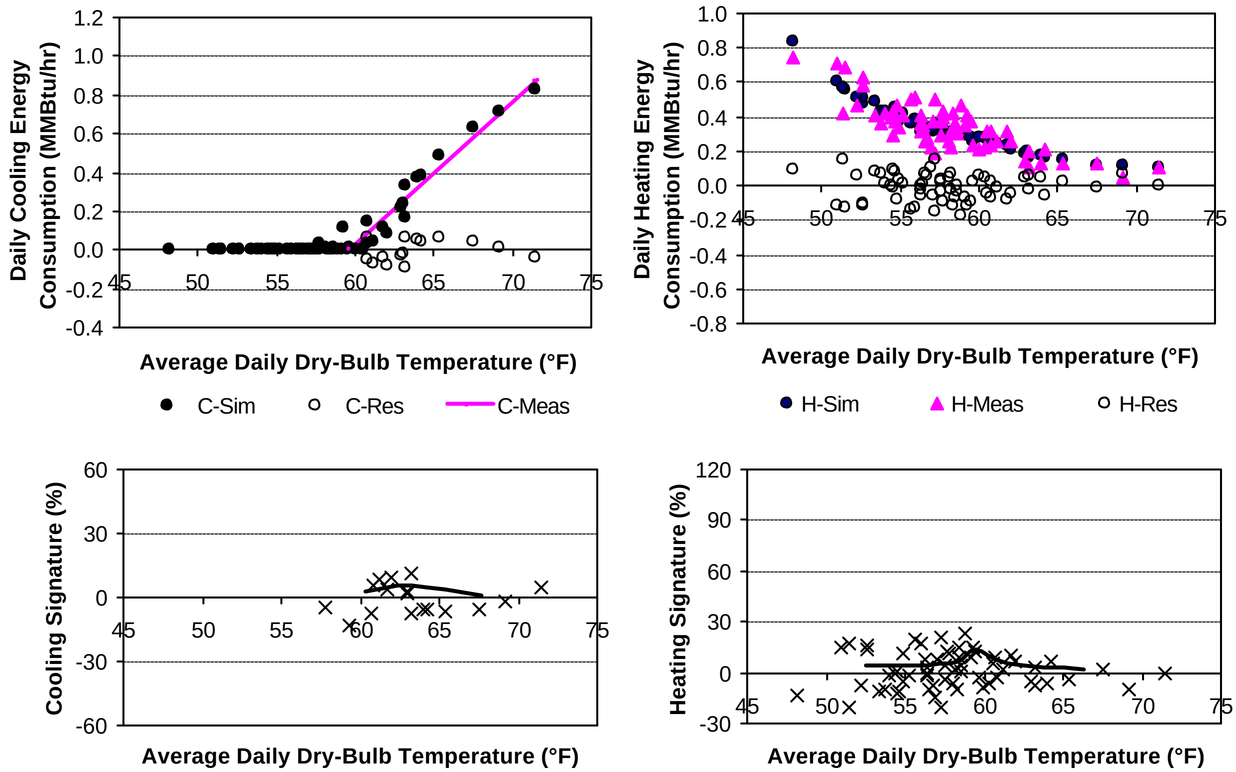


Figure 25. Calibrated simulation charts for case study 1

The bulge in the middle of the heating calibration signature is due to the way the temperature range was divided into small intervals of equal numbers of data points. It turned out that the bulge corresponded to an interval where most of the signature data points were higher than the neighboring data points. They would have cancelled out within a larger or shifted temperature interval.

Otherwise, the residuals are randomly scattered around zero and calibration signatures show no trend with temperature for both cooling and heating. The RMS errors have also been reduced to very small values, i.e. 0.06 and 0.07 MMBtu/hr respectively for cooling and heating. Table 4 shows a summary of the calibration steps. The mean Bias error (MBE) is shown for each calibration step for both cooling and heating. It has been reduced from 0.12 to 0.004 MMBtu/hr for cooling and from -0.33 to 0.005 MMBtu/hr for heating during the calibration process.

Table 4. Summary of calibration steps

Simulation parameter and alteration	Heating (MMBtu/hr)		Cooling (MMBtu/hr)	
	RMSE	**MBE**	**RMSE**	**MBE**
Initial simulation	0.36	-0.33	0.13	0.12
Minimum air flow rate: 0.34 → 0.8 cfm/ft^2	0.28	-0.25	0.13	0.12
Internal gain (average): 1.8 → 1.25 W/ft^2	0.12	-0.016	0.11	0.09
Outside air flow rate: 0.28 → 0.42 cfm/ft^2	0.10	0.003	0.12	0.10
Cold deck temperature: 64 → 66°F, and room temperature: 72 → 73.5°F	0.09	-0.009	0.06	0.004
Envelope U-value: Increased by 20% ◆ Exterior wall and roof: 0.073 → 0.088 $Btu/ft^2.hr.°F$ ◆ Window: 0.34 → 0.41 $Btu/ft^2.hr.°F$	0.08	0.012	0.06	0.005
Hourly calibration ◆ Internal gain: 1.25 av. → 1.42 W/ft^2 max. ◆ Internal gain profile: Figure 24 (right)	0.07	0.005	0.06	0.004

We notice that the calibration process in this case study was rather focused on heating energy consumption, and that was due to the large heating RMSE in the initial simulation (0.36 MMBtu/hr compared to 0.13 MMBtu/hr for cooling). It took two calibration steps to bring it down to the level of the cooling RMSE. This is because reasonable alterations in input parameters produce limited changes in total energy consumption (expect for adding or removing an economizer as can be seen in Appendix D-3).

The calibrated simulation RMS errors were very low for this case study. But, simulation signature data points were quite high (± 10 % for cooling and ± 25 % for heating). This is due to the low energy consumption. In fact, the maximum daily average energy consumption was 0.8 MMBtu/hr for cooling and heating. For the sake of comparison, the maximum daily average energy consumption for a building with a comparable conditioned floor area in College Station, TX - namely the Zachry Engineering Center presented in the second case study - is 6.5 MMBtu/hr for cooling and 2.5 MMBtu/hr for heating. This consumption level would have produced signatures in the range of ± 1 % for cooling and ± 9 % for heating with the RMS errors of this case study.

2. Case Study 2: Zachry Engineering Center

Step 1. The Zachry Engineering Center (ZEC), shown in figure 26, is a Texas A&M University campus building. It is simulated in this case study to illustrate real building calibration using the proposed methodology. The building consists of four floors plus an unconditioned parking basement. It was constructed in the early 1970s and is a heavy structure with 6-inch concrete floors and insulated exterior walls made of pre-cast concrete and porcelain-plated steel panels. About 12% of the exterior wall area is covered with single-pane bronze-tinted glazing. The windows are recessed approximately 24 inches from the exterior walls, which provides some shading. Approximately 3,100 ft^2 of northeast-facing clerestory windows admit daylight into the core of the building. Measured energy consumption and weather data were retrieved from the Energy Systems Laboratory's database.

Figure 26. Zachry Engineering Center (ZEC)

Step 2. AirModel was used for this case study and the simulation was conducted using 1994 data. Daily average dry-bulb temperatures (T_{db}) for the simulation period are shown in the left hand chart of figure 27. The right hand chart shows relative humidity (RH) as a function of dry-bulb temperature.

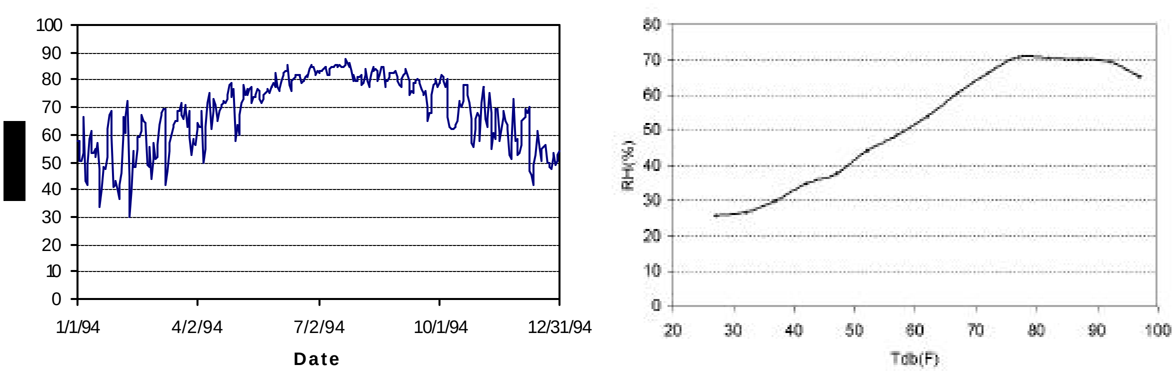


Figure 27. College Station, TX weather conditions for the simulation period

The input parameters used in the initial simulation are summarized in Table 5. They were measured, approximated or retrieved from multiple sources. As AirModel can accept a maximum of three vacation periods, so the longest vacation periods have been modeled and data during the others was eliminated.

Table 5. Initial simulation input parameters for ZEC case study

Parameter	**Value**
AHU type	DDVAV
Conditioned floor area	260,000 ft^2
Interior zone ratio	0.66
Occupied period	8 am to 6 pm
Vacation periods	Jan 4 to 16, May 15 to 29 and August 10 to 28
Exterior wall and roof area	115,040 ft^2
Average exterior wall and roof U-value	0.08 Btu/ft^2.hr.°F
Window area	25,308 ft^2
Window U-value	0.70 Btu/ft^2.hr.°F
Design room temperature	75 °F
Minimum air flow rate	0.5 cfm/ft^2
Outside air flow rate	0.2 cfm/ft^2
Economizer range	None
Average internal heat gain	3.1 W/ft^2
Solar gains (linear between defined points)	0.08 MMBtu/h at 20 °F, and 0.20 MMBtu/h at 110 °F
Average occupancy	180 ft^2/person
Difference between return and room air temperatures	2 °F
Cold deck temperature	55 °F
Hot deck temperature schedule (linear between defined points and constant outside lower and higher limits)	110 °F at T_{OA}=20 °F 90 °F at T_{OA}=42 °F 65 °F at T_{OA}=62 °F
Preheat location	Outside air

Step 3. The ESL database collects hourly energy consumption and weather data in 15-min intervals for this building. Therefore measured data had to be converted to hourly data for the simulation and then to daily data for the calibration.

Step 4. The residuals, the RMS errors and the calibration signatures were calculated for the initial simulation. The RMS errors were 15.4 and 7.0 MMBtu/day respectively for cooling and heating energy consumption.

Step 5. Figure 28 shows the initial simulation charts. The two charts on the left hand side are cooling charts and the two charts on the right hand side are heating charts. The upper ones show simulated (sim) and measured (meas) daily energy consumption, as well as the residuals (res) as defined in equation 2. The lower graphs show calibration signatures as defined in equation 1. The purpose of the solid line in the calibration signatures is to reveal the trend of the scattered data points, which makes it easier to compare the calibration signature to characteristic signatures.

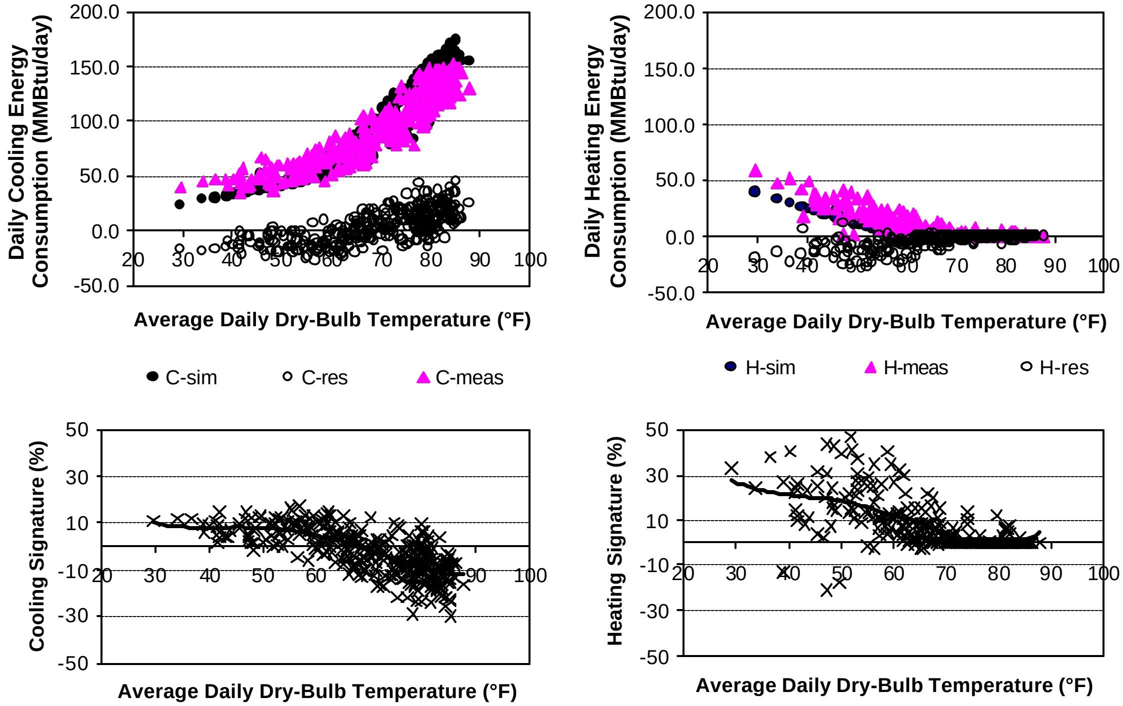


Figure 28. Initial simulation charts for case study 2

Step 6 Since College Station, TX weather is quite different from California weather, it was necessary to generate characteristic signatures for this building. This was done following the procedure described in appendix G. Based on the characteristics of this case study, the input parameters that were considered are the minimum air flow rate (V_{min}), internal heat gain (Q_{int}), outside air flow rate for the interior and exterior zones (respectively $V_{oa(int)}$ and $V_{oa(int)}$), room temperature setpoint (T_{room}), wall and windows U-values, hot deck temperature (T_h) and cold deck temperature (T_c). 5°F temperature bins were used to generate the characteristic signatures. Figure 29 shows the characteristic signatures generated for this case study. Parameter changes are shown at the top of each signature chart.

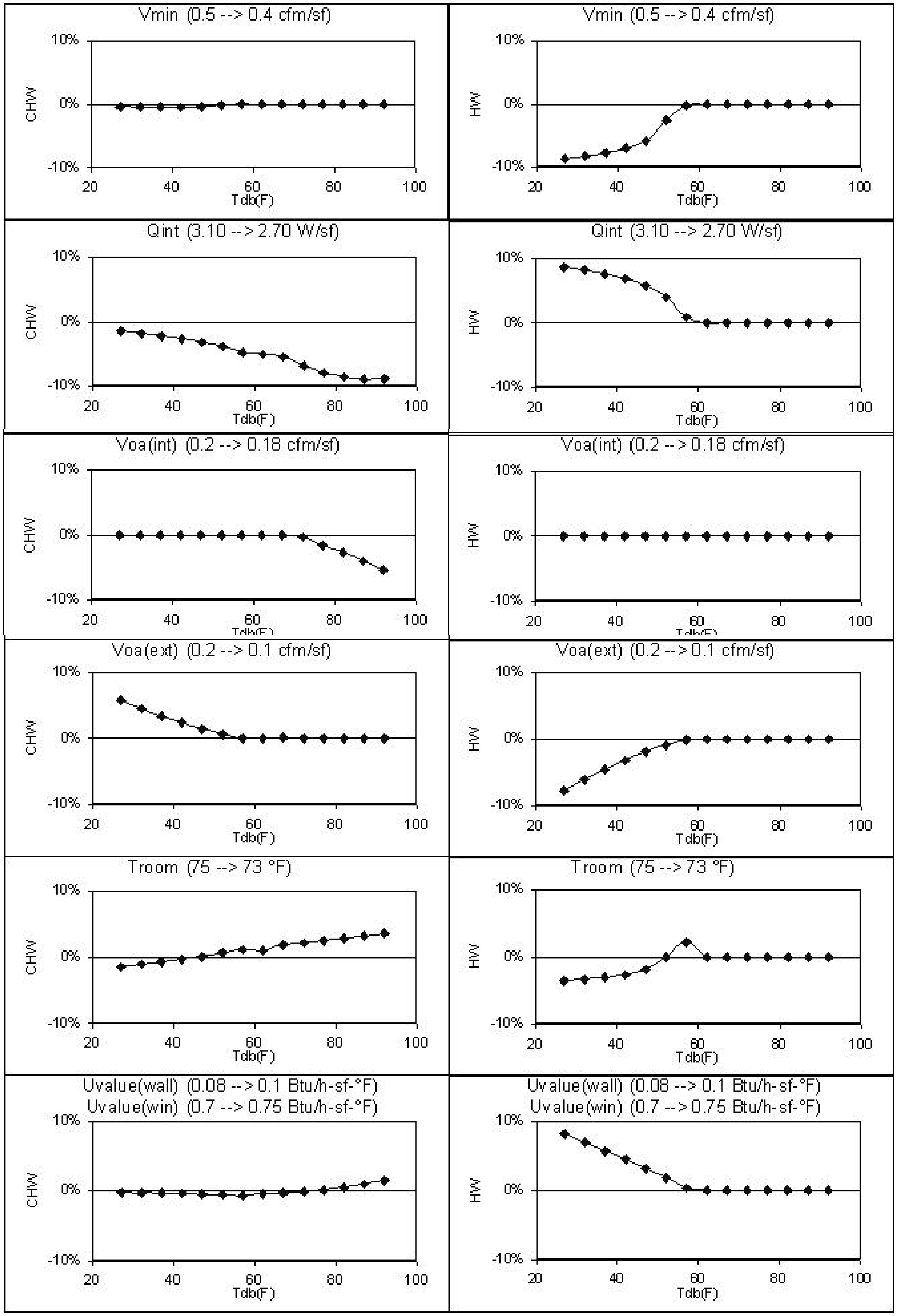


Figure 29. Characteristic signatures for Zachry building

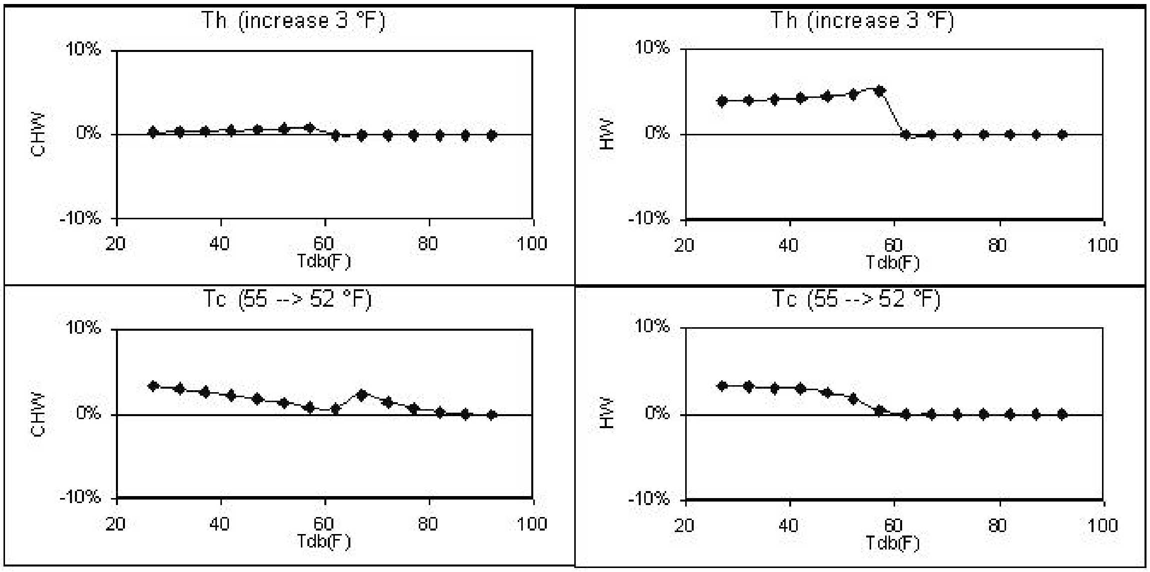


Figure 29. Characteristic signatures for Zachry building (continued)

Examining the calibration signatures in figure 28, we notice that cooling energy consumption needs to be increased by about 10% in the lower temperature range and decreased by about 10% in the higher temperature range. Heating energy consumption needs to be increased by about 30% in the lower temperature range. These calibration signatures can be matched by combining the characteristic signatures of figure 29 for increasing hot deck temperature, decreasing cold deck temperature and decreasing internal heat gain.

Step 7. To determine the input parameters that should be changed, and the amount of change, the magnitudes and patterns of the characteristic signatures should be compared with those of the cooling and heating calibration signatures. It appears that decreasing internal heat gain from 3.1 to 2.7 W/ft^2 (0.4 W/ft^2 as in the signature), increasing the hot deck temperature by 5 °F for the entire schedule (vs. 3 °F in the signature), and lowering the cold deck temperature by 3 °F may combine to increase hot water consumption increase by about 17% at low outside air temperatures. These parameter changes should also decrease the chilled water consumption when the outside air temperature is high. These changes would also increase chilled water (CHW) consumption when outside air temperature is low, but probably by only 5%. Thus we are still looking for another 5% CHW increase when outside air temperature is low and 13% hot water (HW) consumption increase. We therefore choose to decrease exterior zone outside air flow rate (from 0.2 to 0.1 cfm/ft^2) and increase wall and window U-values (from 0.08 to 0.1 and from 0.7 to 0.75 respectively). We must be careful to keep all parameter values physically reasonable. For example, a cold deck temperature below 50 °F is unlikely.

Step 8. The results of the first iteration are shown in figure 30. The RMSE values for CHW and HW decreased from 15.4 and 7.0 MMBtu/day to 12.0 and 5.6 MMBtu/day respectively. The MBE values for CHW and HW changed from 4.0 and -3.5 MMBtu/day to -7.5 and -2.4 MMBtu/day. The shape of the CHW calibration signature flattened significantly. However the HW calibration signature shows that HW consumption still needs to increase.

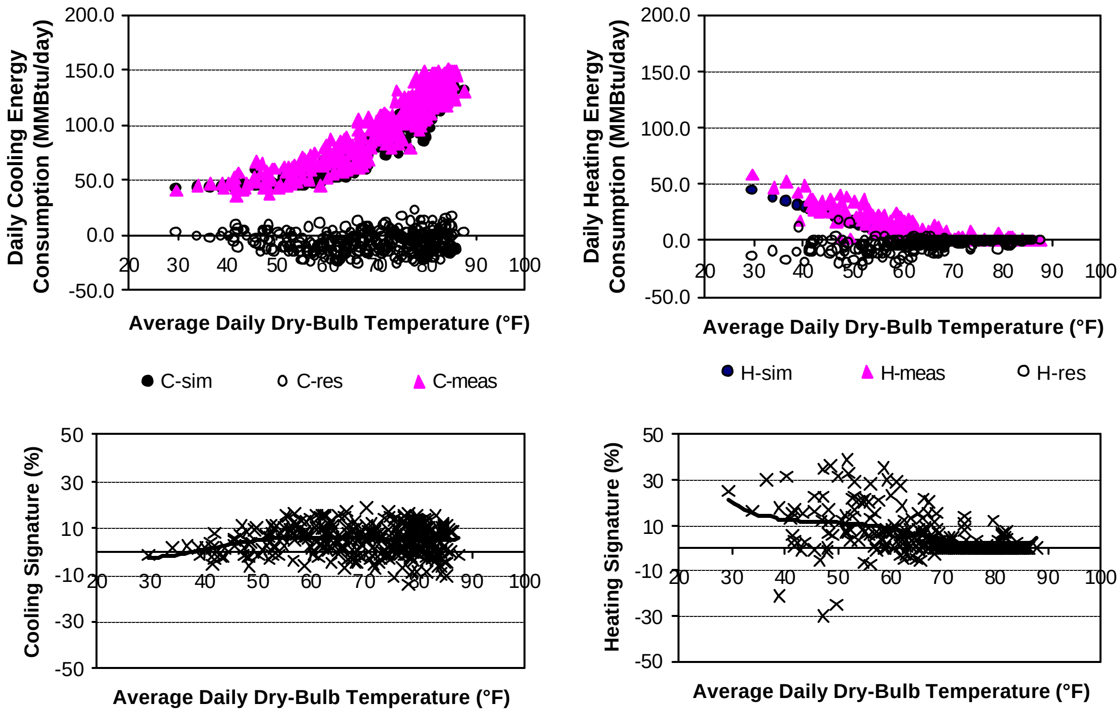


Figure 30. Cooling and heating simulation charts after the first alteration

Iteration 2. According to the calibration signature of figure 30, the CHW consumption need to increase by 7% when the outside air temperature is above 50 °F. The HW consumption needs to increase by 5-23% when the outside air temperature is lower than 70 °F. Examining the characteristic signatures indicates that changing internal heat gain and hot deck temperature may make both simulated CHW and HW close to the measured values. It was decided to increase internal heat gain from 2.7 to 3.0 W/ft^2, and modify the hot deck temperature schedule so it is 130 °F when outside air temperature is 20 °F or below, 105 °F when outside air is 42 °F, 90 °F when outside air is 50 °F, and 70 °F when outside air is 62 °F or above.

The results of the Iteration 2 are shown in figure 31. The RMSE for CHW and HW decreased from 12.0 and 5.6 MMBtu/day to 9.5 and 5.0 MMBtu/day respectively. The MBE of CHW and HW changed from -7.5 and -2.4 MMBtu/day to -0.5 and -1.8 MMBtu/day.

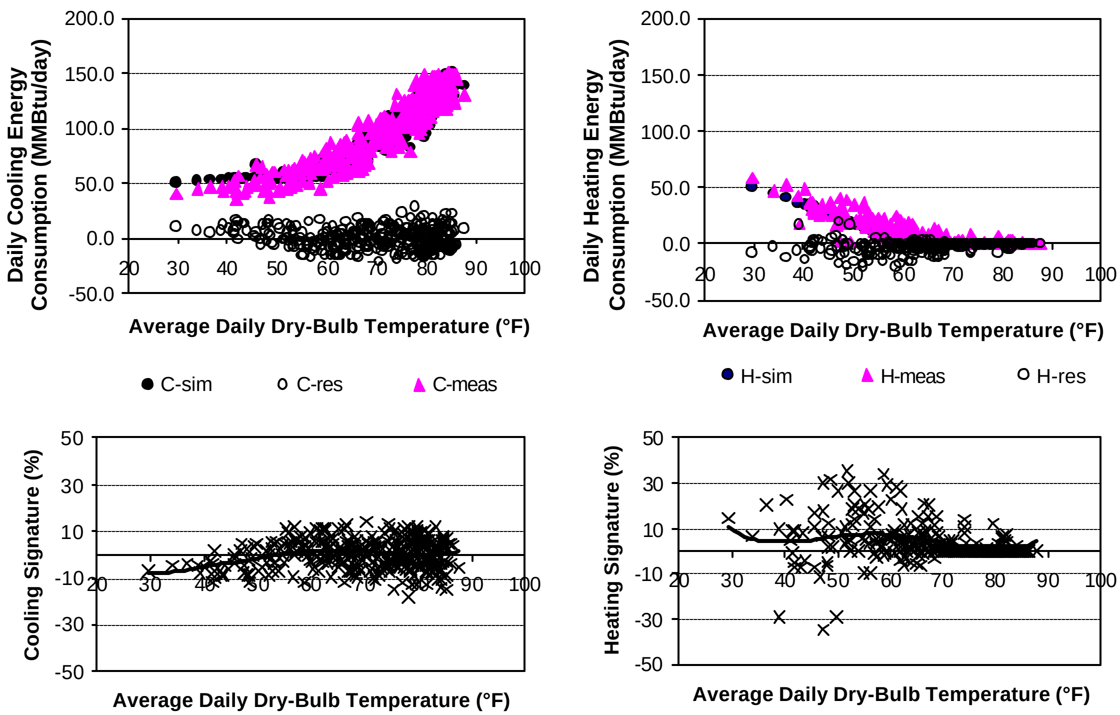


Figure 31. Cooling and heating simulation charts after iteration 2

Iteration 2 was successful in shifting the CHW and HW consumption upward. However the calibration signatures are still not uniformly close to zero.

Iteration 3. The CHW and HW signatures from iteration 2 show that during mild and hot weather conditions, the simulation model is well calibrated; however when the weather is cold, simulated CHW consumption is excessive and HW consumption is low. Based on the calibration signatures, it was decided to make the following changes. The exterior zone outside air flow rate was increased from 0.1 to 0.14 cfm/ft^2, window U-value was increased from 0.75 to 1.0 Btu/ft^2.hr.°F, and the hot deck temperature schedule modified to 95 °F when outside air temperature is 50 °F, 75 °F when outside air temperature is 62 °F, and 70 °F when outside air temperature is 85 °F or above.

Iteration 3 improved the calibration as shown in figure 32. The RMSE for CHW did not change from 9.5 MMBtu/day. However the CHW calibration signature pattern has been stabilized. The RMSE for HW decreased from 5.0 to 4.5 MMBtu/day. The MBE values for CHW and HW changed from -0.5 and -1.8 MMBtu/day to -1.0 and 0.0 MMBtu/day. There is still more room to improve the HW signature at low outside temperatures and improve the MBE for CHW.

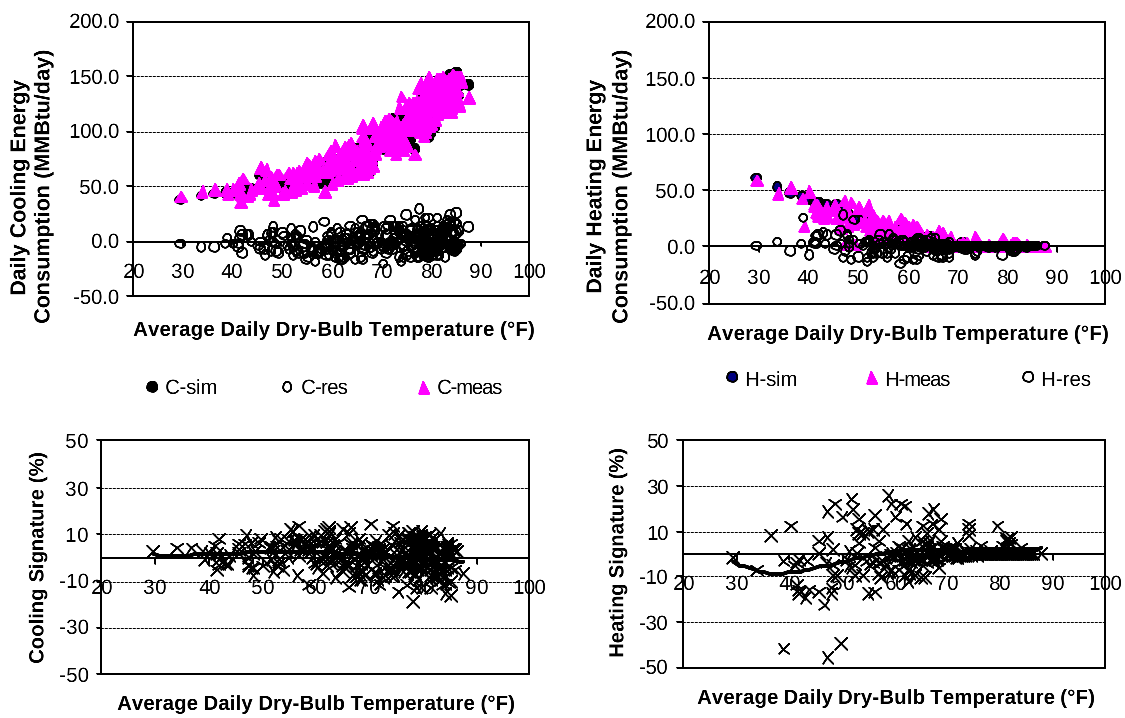


Figure 32. Cooling and heating simulation charts after iteration 3

Iteration 4. The HW calibration signature from Iteration 3 (figure 32) shows that for mild weather conditions, the simulation is well calibrated, but simulated cold weather HW consumption is too high. The HW characteristic signature for the U-value of the building is opposite the shape of the HW calibration signature. To lower the HW consumption for cold weather and fine tune the CHW, it was decided to change window U-value from 1.0 to 0.85 Btu/ft^2.hr.°F.

Iteration 4 (figure 33) improved the HW calibration signature and the RMSE values for CHW and HW decreased from 9.5 and 4.5 (MMBtu/day) to 9.4 and 4.4 (MMBtu/day) respectively. The MBE of CHW and HW changed from -1.0 and 0.0 (MMBtu/day) to –1.0 and –0.3 (MMBtu/day).

There is still room for small improvements in CHW and HW consumption that may be provided by hourly calibration.

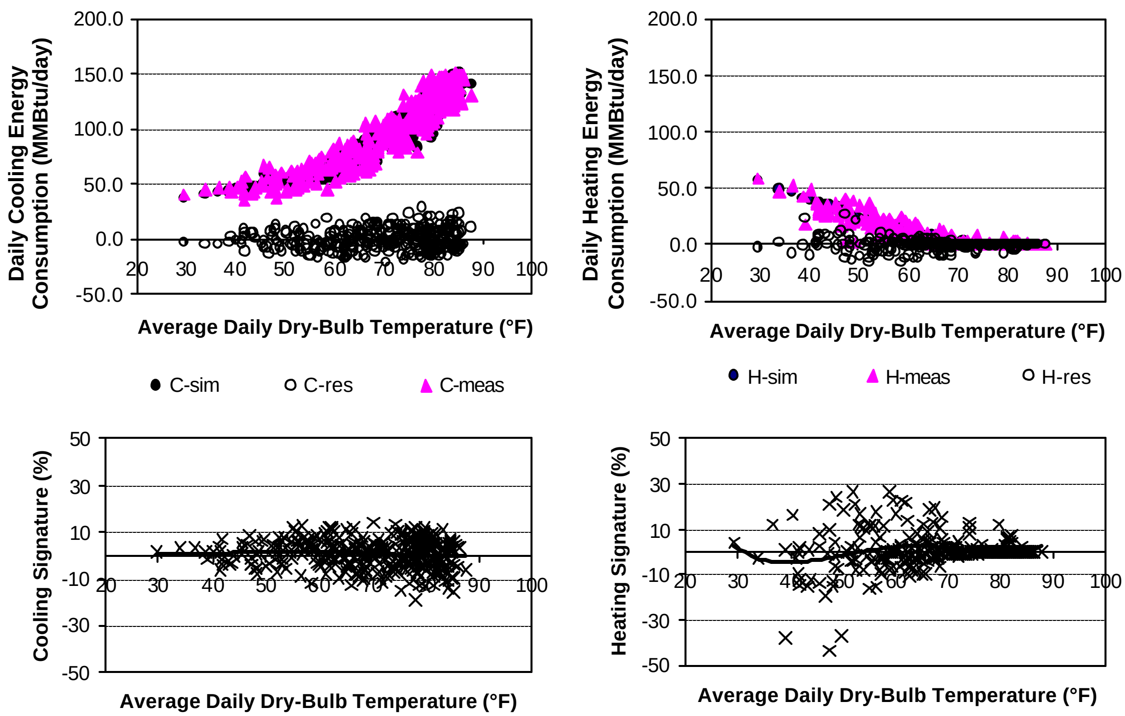


Figure 33. Cooling and heating simulation charts after iteration 4

Step 9. The results of iteration 4 were quite good. However hourly calibration might fine-tune the simulation model. The Zachry Engineering Center includes offices, classrooms, laboratories and computer rooms and is open 24 hours per day, 365 days per year with heaviest occupancy during normal working hours between 8 a.m. and 6 p.m. on weekdays.

The available metered data for electricity consists of Whole Building Electricity consumption (WBE) and Motor Control Center (MCC) electricity consumption. The MCC electricity is the consumption of the HVAC fans and pumps, which is largely consumed in unconditioned zones. Therefore the internal load for the building due to the electricity consumption can be approximated as (WBE – MCC). The MCC electricity consumption was relatively constant throughout 1994 at approximately 200kWh/h.

Figures 34 to 36 show the internal load pattern vs. the time of the day for weekdays, weekends, and university vacation periods when classes are not in session. The curves on the measured electricity graphs (left side) connect the average values for the electricity consumption for each hour of the day. The occupancy schedules (right side) are calculated from the averaged electricity consumption by dividing the averaged electricity consumption values by the maximum hourly average electricity consumption for the year (1075.95kWh/h).

The maximum value of measured (WBE – MCC) is 4.13 W/ft^2 (1075.95 kWh/h for the building). The original occupancy schedule was 1.0 for every hour of the year with a calibrated average internal heat gain value of 3.0 W/ft^2.

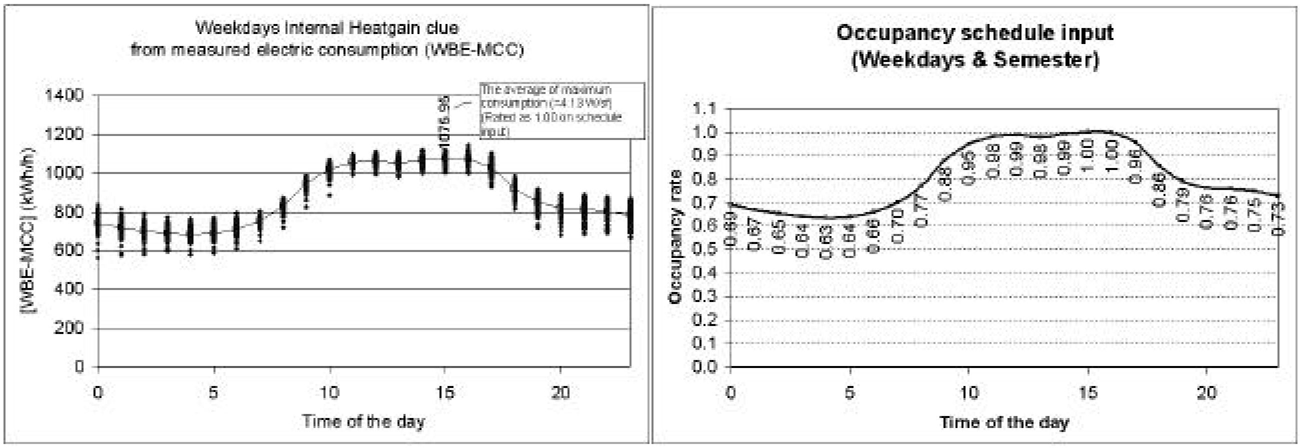


Figure 34. Measured electricity consumption [WBE-MCC] for weekday periods and occupancy schedule input based on the [WBE-MCC] pattern for weekdays.

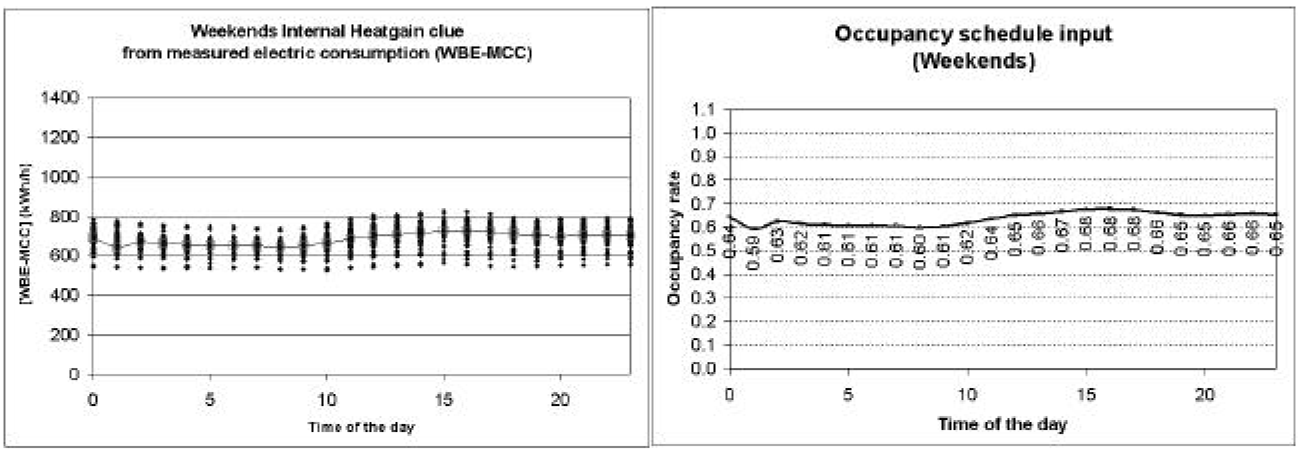


Figure 35. Measured electricity consumption [WBE-MCC] for weekend periods and occupancy schedule input based on the [WBE-MCC] pattern for weekends.

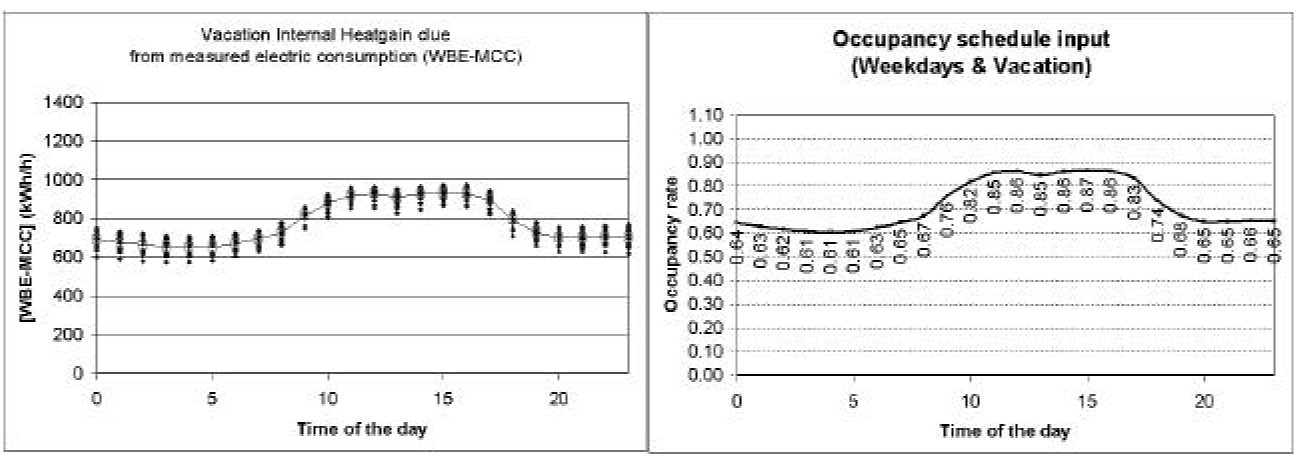


Figure 36. Measured electricity consumption [WBE-MCC] for vacation periods and occupancy schedule input based on the [WBE-MCC] pattern for vacation periods.

The results of the hourly calibration are shown in figure 37. While the RMSE for HW did not change from 4.4 MMBtu/day, the RMSE for CHW improved from 9.4 MMBtu/day to 7.2 MMBtu/day. The MBE is unchanged from the last iteration at -1.0 and -0.3 MMBtu/day for CHW and HW respectively. The calibration is finished.

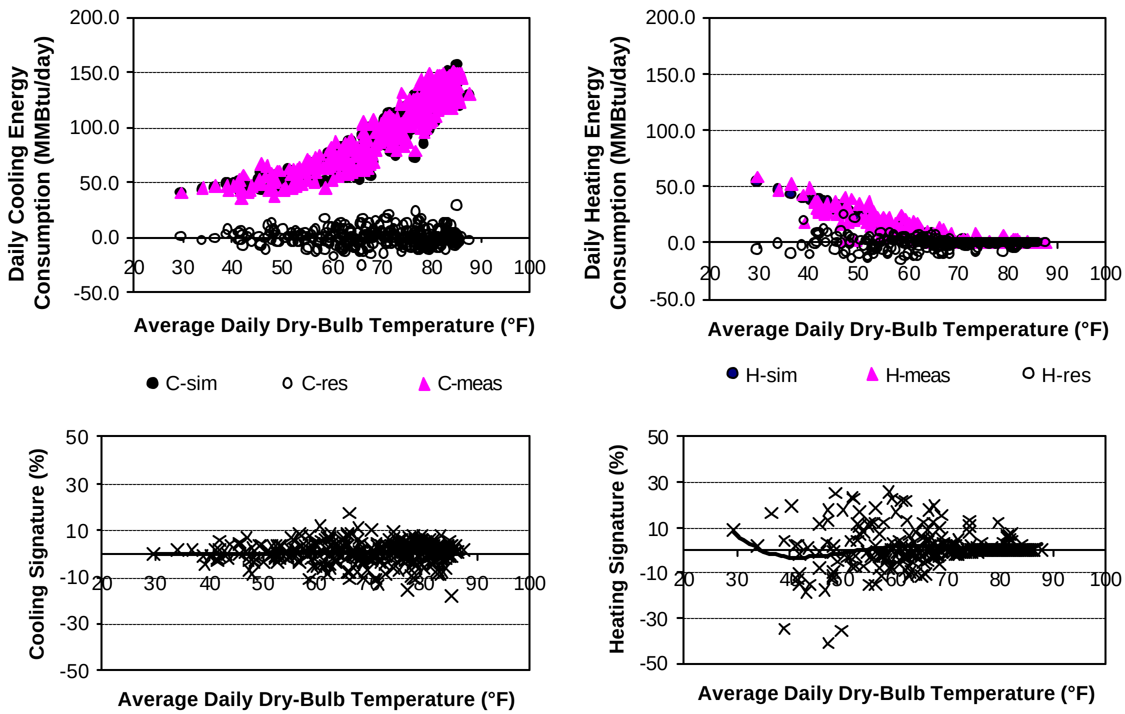


Figure 37. Calibrated simulation charts for case study 2

The calibration procedure using calibration signatures has been illustrated for the Zachry Engineering Center at Texas A&M University. Hourly fine-tuning with measured electricity consumption inside the conditioned zone appreciably reduced the CHW RMSE. Five calibration steps, reduced the RMSE for CHW and HW from 15.4 and 7.0 MMBtu/day to 7.2 and 4.4 MMBtu/day respectively.

This calibration method requires some engineering sense of appropriate values, but can significantly speed the process, even for engineers without a great deal of simulation experience. The use of calibration signatures and characteristic signatures help decide which parameter(s) should be changed and gives some indication of the size of change required.

A summary of the calibration iterations is shown in Table 6.

Table 6. Summary of calibration steps

Simulation parameter and alteration		Cooling (MMBtu/day)		Heating (MMBtu/day)	
		RMSE	**MBE**	**RMSE**	**MBE**
Initial simulation:		15.4	4.0	7.0	-3.5
Internal heat gain (av.): Outside air flow (ext.): Wall U-value: Window U-value: Hot deck temperature: Cold deck temperature:	3.1 → 2.7 W/ft^2 0.2 → 0.1 cfm/ft^2 0.08 → 0.1 $Btu/ft^2.hr.°F$ 0.7 → 0.75 $Btu/ft^2.hr.°F$ Increased by 5°F Decreased by 3°F	12.0	-7.5	5.6	-2.4
Internal heat gain: Hot deck temperature:	2.7 → 3.0 W/ft^2 130 °F at T_{OA}=20 °F 105 °F at T_{OA}=42 °F 90 °F at T_{OA}=50 °F 70 °F at T_{OA}=62 °F	9.5	-0.5	5.0	-1.8
Outside air flow (ext.): Window U-value: Hot deck temperature:	0.1 → 0.14 cfm/ft^2 0.75 → 1.0 $Btu/ft^2.hr.°F$ 130 °F at T_{OA}=20 °F 105 °F at T_{OA}=42 °F 95 °F at T_{OA}=50 °F 75 °F at T_{OA}=62 °F 70 °F at T_{OA}=85 °F	9.5	-1.0	4.5	0.0
Window U-value:	1.0 → 0.85 $Btu/ft^2.hr.°F$	9.4	-1.0	4.4	-0.3
Hourly calibration: ◆ Internal gain: ◆ Occupancy schedule:	 3.0 (av.) → 4.13 W/ft^2 (max.) Figures 34-36 (right)	7.2	-1.0	4.4	-0.3

CONCLUSIONS

This manual describes a method that can be used to facilitate the calibration of a building system simulation to measured data. The method uses a graphical format that intuitively summarizes and describes the differences between the simulation results and the measured data, referred to as a Calibration Signature. By creating a library of shapes for certain known errors, we can provide clues to the analyst to use in identifying what simulation input errors may be causing the discrepancies. These are referred to as Characteristic Calibration Signatures.

This manual describes how the signatures are defined, and how they are used in calibration. It provides two fairly simple examples of their use, based on synthetic data, and provides two real-world examples that illustrate how to handle additional challenges in the calibration process. The Characteristic Calibration Signatures are provided in the Appendices for four different system types, and for three different California climates.

This method was found to be quite useful in several examples, and its use should enable a broader array of analysts to produce better quality building simulations. These more reliable simulations can be used for a host of purposes, including retrofit expected savings analysis, building optimization, commissioning, and fault detection.

REFERENCES

Cho, S.Y., "The Persistence of Savings Obtained from Commissioning Existing Buildings," M.S. Thesis, Mechanical Engineering Department, Texas A&M University, 2002.

Claridge, D.E., Turner, W.D., Liu, M., Deng, S., Wei, G., Culp, C., Chen, H. and Cho, S.Y., "Is Commissioning Once Enough?," *Solutions for Energy Security & Facility Management Challenges: Proc. of the 25th WEEC*, Atlanta, GA, Oct. 9-11, 2002, pp. 29-36.

Department of Architecture, Texas A&M University, (1984). *Bin Weather Data: For Simplified Energy Calculations and Variable Base Degree Day Information*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Diamond, S., and B. Hunn, (1981). *Comparison of DOE-2 Computer Program Simulations to Metered Data from Seven Commercial Buildings.* ASHRAE Transactions, Vol. 87, Pt 1.

Duffie, J.A., and Beckman, W.A., (1991). *Solar Engineering of Thermal Processes*. (2nd ed.). New York, NY: John Wiley & Sons.

Eley Associates, (2001). *Oakland Administration Building Energy Performance Contract*. San Francisco, CA.

Haberl, J. and T. Bou-Saada, (1998). *Procedures for Calibrating Hourly Simulation Models to Measured Building Energy and Environmental Data*. ASME Journal of Solar Energy Engineering, Vol. 120, pp. 193-204, August.

IPMVP, (2001). IPMVP Committee, *International Performance Measurement & Verification Protocol: Concepts and Options for Determining Energy and Water Savings*, Vol. 1, U.S. Dept. of Energy, DOE/GO-102001-1187, 86 pp., January.

Kaplan, M., J. McFerran, J. Jansen, and R. Pratt, (1992). *Reconciliation of a DOE2.1c Model with Monitored End-use Data from a Small Office Building*. ASHRAE Transactions Vol. 96, Pt 1.

Knebel, D.E., (1983). *Simplified Energy Analysis Using the Modified Bin Method*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Liu, M and Claridge, D.E., 1995. "Application of Calibrated HVAC System Models to Identify Component Malfunctions and to Optimize Operation and Control Schedules", *Solar Engineering 1995 - Proceedings of the 1995 ASME/JSME/JSES International Solar Energy Conference*, Vol. 1, Maui, Hawaii, pp. 209-217, March 19-24.

Liu, M., (1997). *User's Manual for Air Side Simulation Programs (AirModel).* College Station, TX: Energy Systems Laboratory, Texas A&M University.

Liu, M. and D.E. Claridge, (1998). *Use of Calibrated HVAC System Models to Optimize System Operation*. ASME Journal of Solar Energy Engineering, Vol. 120, pp. 131-138.

Liu, M., Wei, G. and Claridge, D. E., (1998). *Calibrating AHU Models Using Whole Building Cooling and Heating Energy Consumption Data.* Washington, D.C.:

Proceedings of the ACEEE 1998 Summer Study on Energy Efficiency in Buildings, Volume 3, American Council for an Energy Efficient Economy, pp. 229-241, 1998.

Liu, M., Claridge, D. and Song, L., 2002. "Potential of On-line Simulation for Fault Detection and Diagnosis in Large Commercial Buildings with Built-up HVAC Systems," submitted to Lawrence Berkeley National Laboratory, July, http://buildings.lbl.gov/hpcbs/pubs/E5P23T2.3T1b.pdf.

Motegi, N., Piette, M.A., and Wentworth, S., (2002). *From Design Through Operations - Multi -Year Results from a New Construction Performance Contract*. Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings.

Motegi, N., (2001). Personal communication, February 2001.

Motegi, N., (2002). Personal communication, February 2002.

Turner, W. D., Claridge, D. E., Deng, S. and Wei, G., 2003. "The Use of Continuous Commissioning[SM] As An Energy Conservation Measure (ECM) for Energy Efficiency Retrofits," Proc. of 11th National Conference on Building Commissioning, Palm Springs, CA, May 20-22, CD

Wei, G., Liu, M., and Claridge, D.E., (1998). *Signatures of Heating and Cooling Energy Consumption for Typical AHUs*. Fort Worth, TX: Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates.

APPENDIX A: DESCRIPTION OF BUILDING AND SYSTEM MODELS USED TO CREATE CHARACTERISTIC SIGNATURES

Characteristic calibration signatures are provided in this manual for four different system types and three different climates:

System Types:	*Climates:*
Single-duct, constant-air-volume (SDCV)	Pasadena
Single-duct, variable-air-volume (SDVAV)	Sacramento
Dual-duct, constant-air-volume (DDCV)	Oakland
Dual-duct, variable-air-volume (DDVAV)	

Figures A-1 and A-2 show schematics of the single-duct and dual-duct systems used to generate the characteristic signatures in this manual. Constant-air-volume systems have constant air flow rate fans, while variable-air-volume systems have variable air flow rate fans.

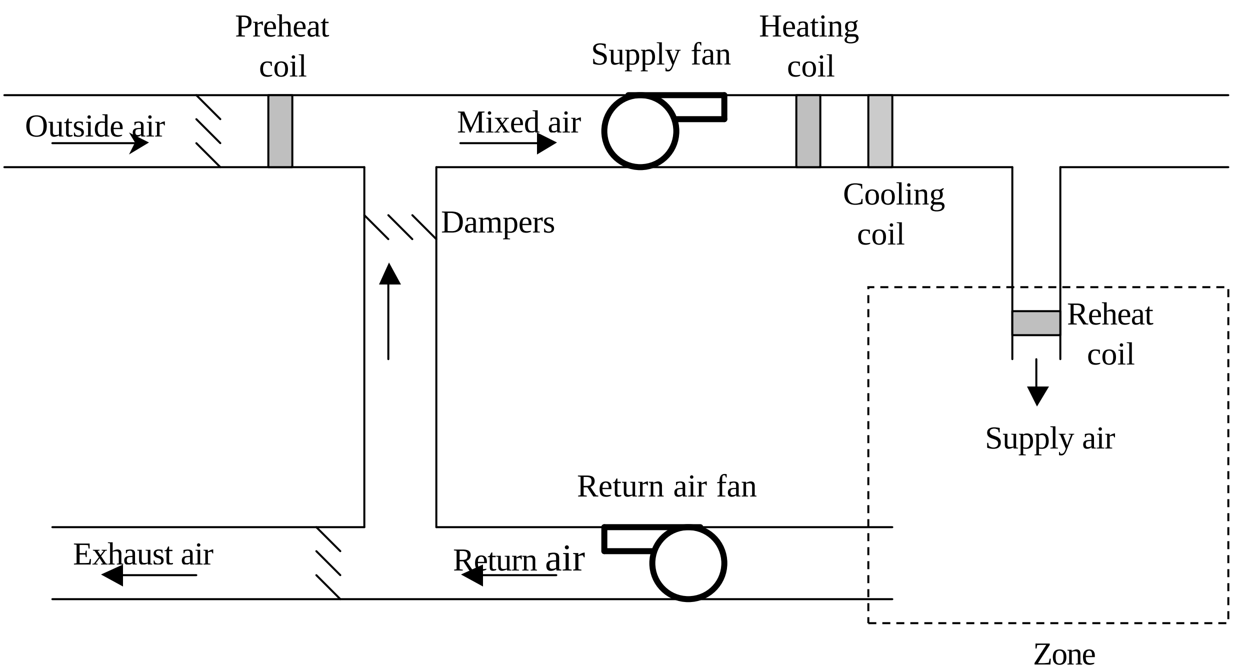


Figure A-1. Schematic of a single-duct air handler

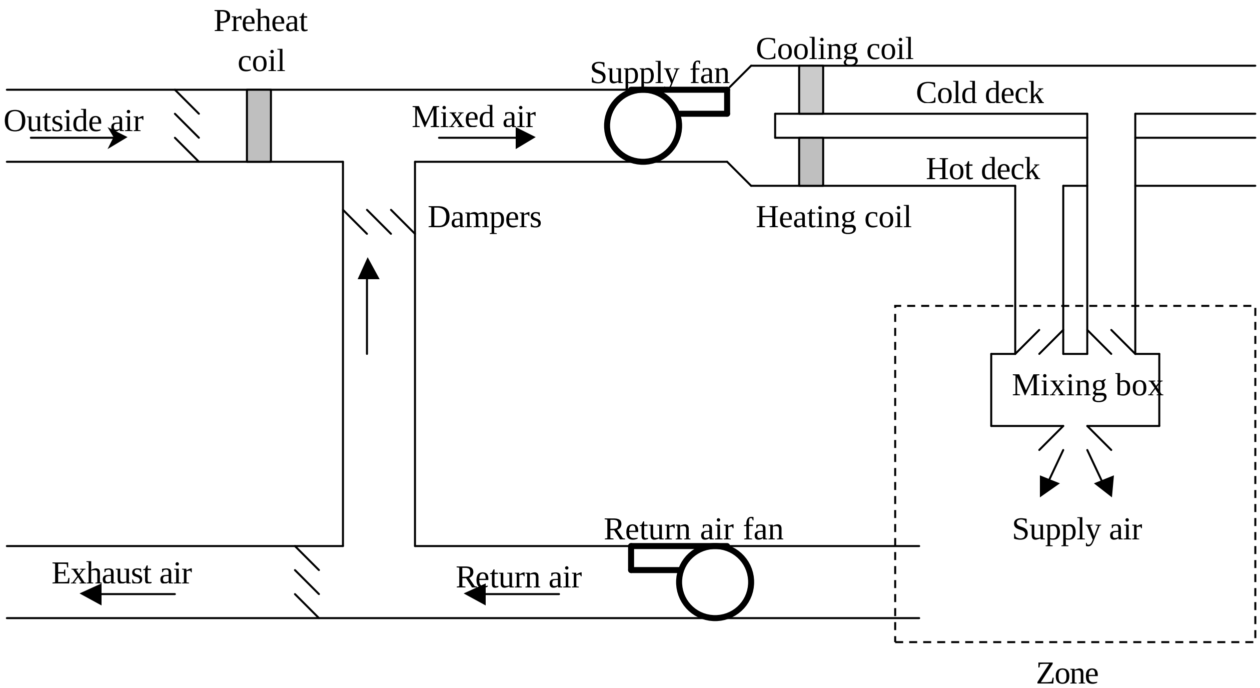


Figure A-2. Schematic of a dual-duct air handler

The operational equations that define the models used for SDCV, SDVAV, DDCV and DDVAV systems are shown respectively in Figures A-3 to A-6, with the nomenclature defined in Table A-1.

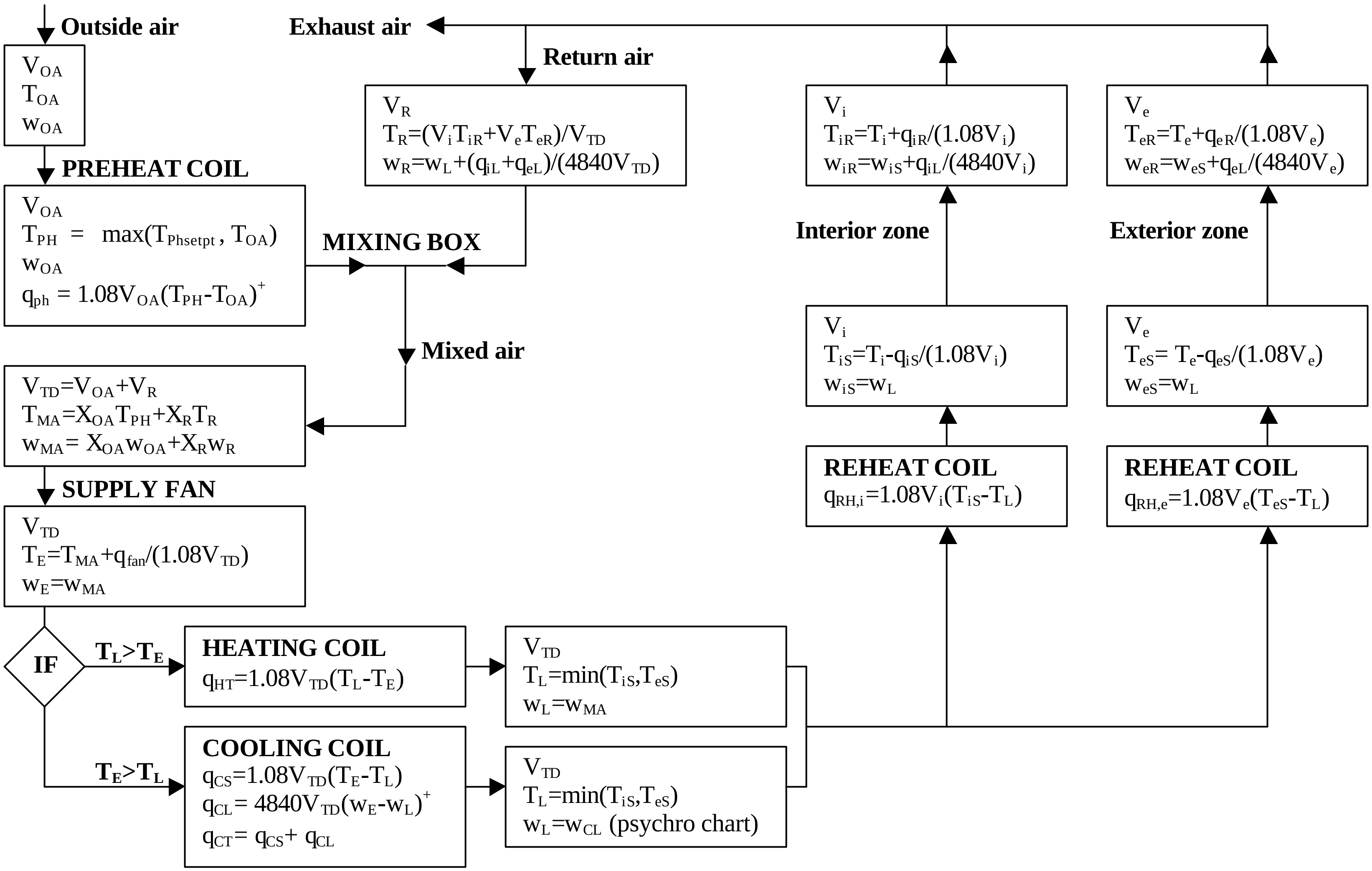


Figure A-3. Operational equations for a SDCV System

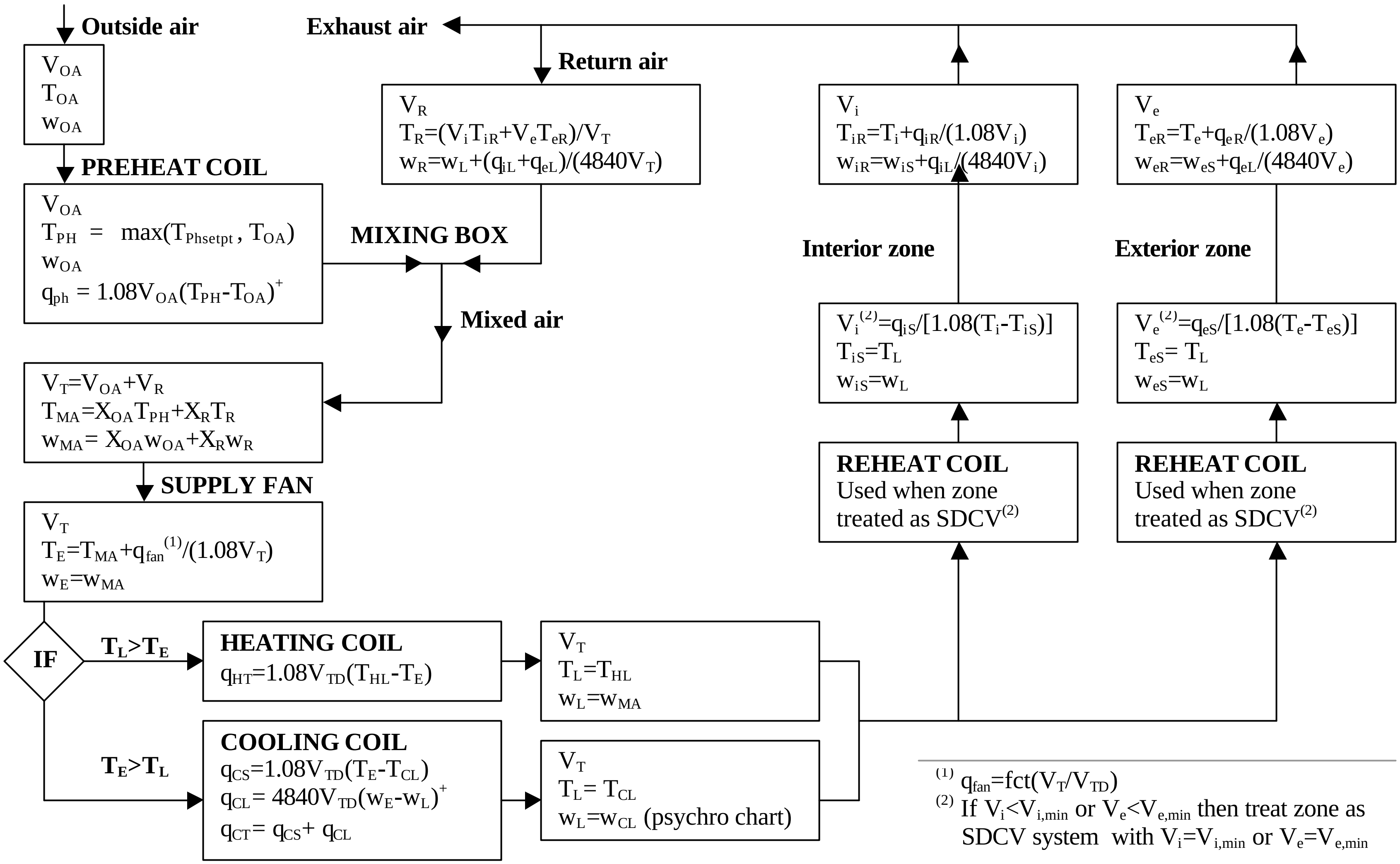


Figure A-4. Operational equations for a SDVAV System

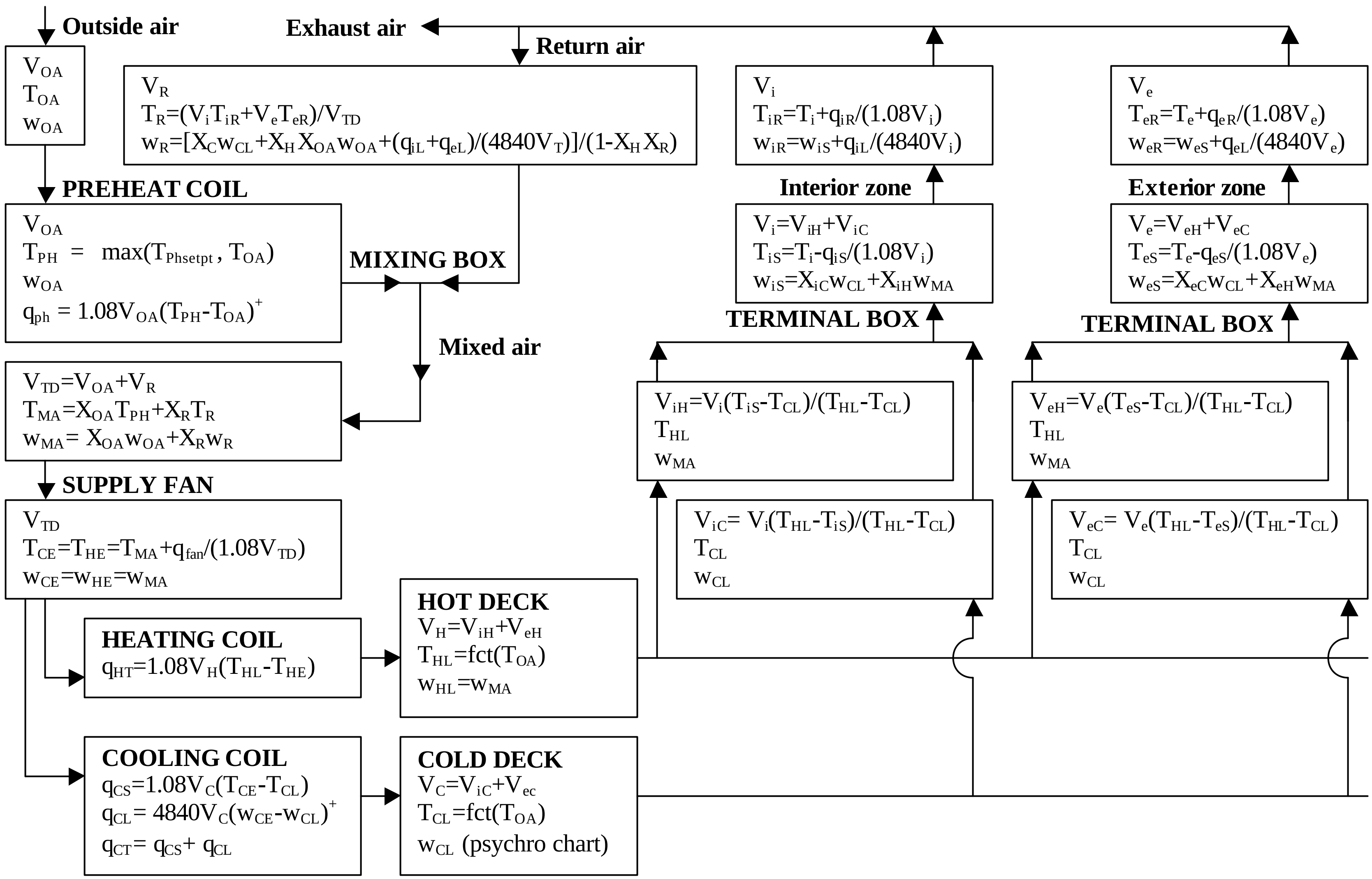


Figure A-5. Operational equations for a DDCV System

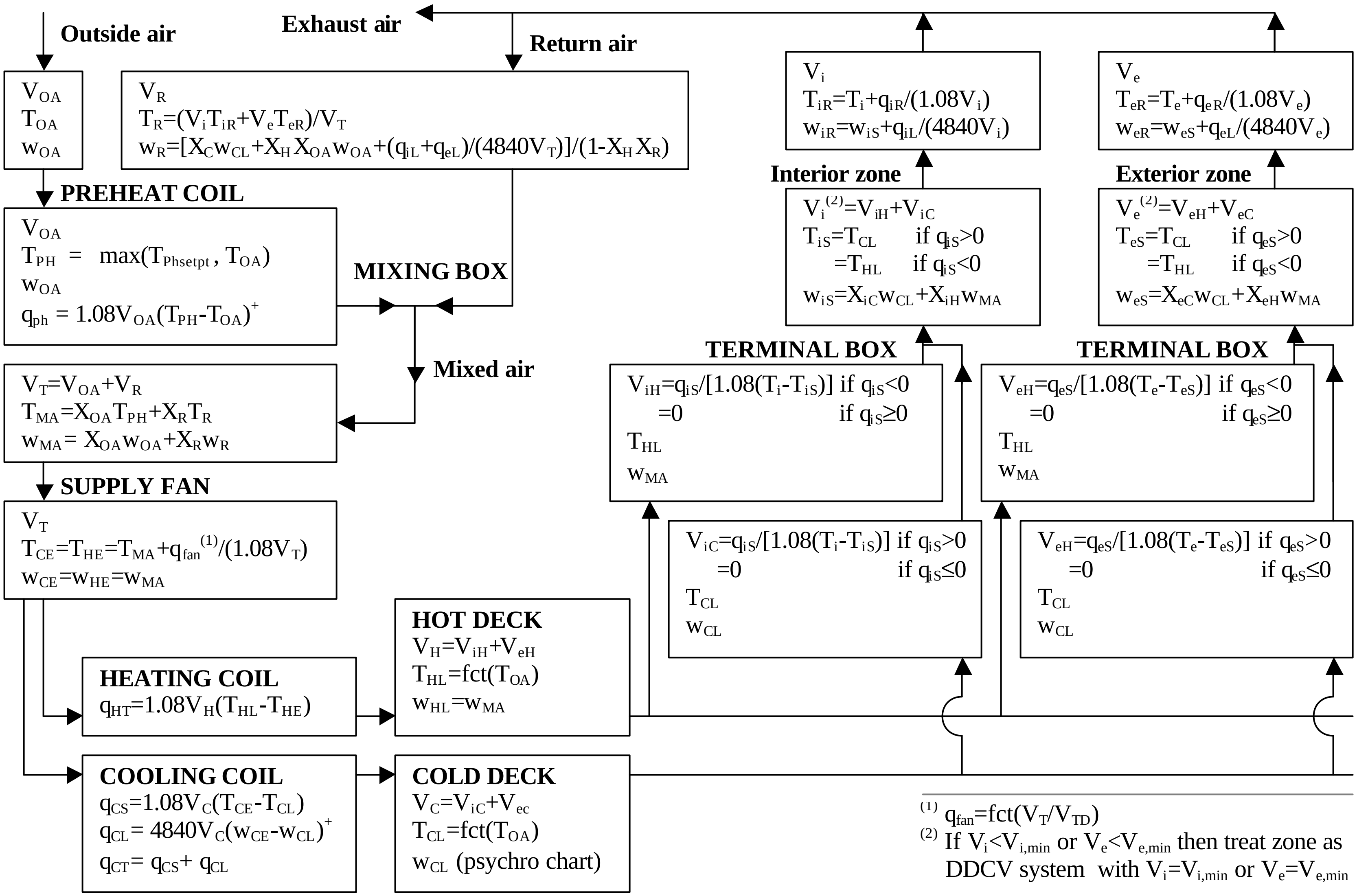


Figure A-6. Operational equations for a DDVAV System

Table A-1. Nomenclature for operational equations

Variable	Definition	Unit
ΔT_{SF}	Supply air fan Temperature rise	°F
q_{CL}	Cooling coil latent load	Btu/hr
q_{CS}	Cooling coil sensible load	Btu/hr
q_{CT}	Cooling coil total load	Btu/hr
q_{eL}	Exterior zone latent load	Btu/hr
q_{eR}	Exterior zone return air heat gain	Btu/hr
q_{eS}	Exterior zone sensible load	Btu/hr
q_{HT}	Heating coil sensible load	Btu/hr
q_{iL}	Interior zone latent load	Btu/hr
q_{iR}	Interior zone return air heat gain	Btu/hr
q_{iS}	Interior zone sensible load	Btu/hr
q_{ph}	Preheat coil load	Btu/hr
$q_{RH,i}$	Interior zone reheat coil load	Btu/hr
$q_{RH,e}$	Exterior zone reheat coil load	Btu/hr
T_{CE}	Cooling coil entering air dry bulb Temperature	°F
T_{CL}	Cooling coil leaving air dry bulb Temperature	°F
T_{e}	Exterior zone design air dry bulb Temperature	°F
T_{E}	Coil entering air dry bulb Temperature	°F
T_{eR}	Exterior zone return air dry bulb Temperature	°F
T_{eS}	Exterior zone supply air dry bulb Temperature	°F
T_{HE}	Heating coil entering air dry bulb Temperature	°F
T_{HL}	Heating coil leaving air dry bulb Temperature	°F
T_{i}	Interior zone design air dry bulb Temperature	°F
T_{iR}	Interior zone return air dry bulb Temperature	°F
T_{iS}	Interior zone supply air dry bulb Temperature	°F
T_{L}	Coil leaving air dry bulb Temperature	°F
T_{MA}	Mixed air dry bulb Temperature	°F
T_{OA}	Outside air dry bulb Temperature	°F
T_{PH}	Preheat coil leaving air dry bulb Temperature	°F
T_{R}	Return air dry bulb Temperature	°F
V_{C}	Cold Deck air volume	ft^3/min
V_{e}	Exterior zone supply air volume	ft^3/min
$V_{e,min}$	Exterior zone minimum supply air volume	ft^3/min

Table A-1. Nomenclature for operational equations (continued)

Variable	Definition	Unit
V_{eC}	Exterior zone cold air volume	ft^3/min
V_{eH}	Exterior zone hot air volume	ft^3/min
V_H	Hot Deck air volume	ft^3/min
V_i	Interior zone supply air volume	ft^3/min
$V_{i,min}$	Interior zone minimum supply air volume	ft^3/min
V_{iC}	Interior zone cold air volume	ft^3/min
V_{iH}	Interior zone hot air volume	ft^3/min
V_{OA}	Outside air volume	ft^3/min
V_R	Return air volume	ft^3/min
V_T	Total air volume	ft^3/min
V_{TD}	Design total air volume	ft^3/min
w_{CE}	Cooling coil entering air humidity ratio	lb_w/lb_a
w_{CL}	Cooling coil leaving air humidity ratio	lb_w/lb_a
w_E	Coil entering air humidity ratio	lb_w/lb_a
w_{eR}	Exterior zone return air humidity ratio	lb_w/lb_a
w_{eS}	Exterior zone supply air humidity ratio	lb_w/lb_a
w_{HE}	Heating coil entering air humidity ratio	lb_w/lb_a
w_{HL}	Heating coil leaving air humidity ratio	lb_w/lb_a
w_{iR}	Interior zone return air humidity ratio	lb_w/lb_a
w_{iS}	Interior zone supply air humidity ratio	lb_w/lb_a
w_L	Coil leaving air humidity ratio	lb_w/lb_a
w_{MA}	Mixed air humidity ratio	lb_w/lb_a
w_{OA}	Outside air humidity ratio	lb_w/lb_a
w_R	Return air humidity ratio	lb_w/lb_a
X_C	Cold Deck air volume ratio = V_C/V_T	Dimensionless
X_{eC}	Exterior zone cold air volume ratio = V_{eC}/V_e	Dimensionless
X_{eH}	Exterior zone hot air volume ratio = V_{eH}/V_e	Dimensionless
X_H	Hot Deck air volume ratio = V_H/V_T	Dimensionless
X_{iC}	Interior zone cold air volume ratio = V_{iC}/V_i	Dimensionless
X_{iH}	Interior zone hot air volume ratio = V_{iH}/V_i	Dimensionless
X_{OA}	Ouside air volume ratio = V_{OA}/V_T	Dimensionless
X_R	Return air volume ratio = V_R/V_T	Dimensionless

A prototypical 6-floor office building was simulated to generate the characteristic calibration signatures. Figure A-7 shows the floor plan of the building. Major characteristics of the building and its systems are shown in Table A-2.

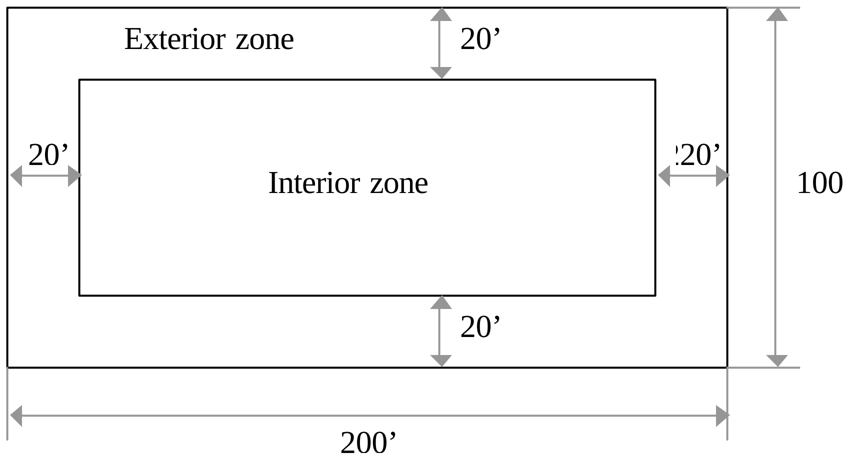


Figure A-7. Building floor plan

Table A-2. Baseline building and system characteristics

Parameter	Baseline value
Conditioned floor area	120,000 ft^2
Interior zone ratio	0.5
Exterior wall area	37,800 ft^2
Exterior wall U-value	0.1 Btu/ft^2.hr.°F
Window area	16,200 ft^2
Window U-value	0.7 Btu/ft^2.hr.°F
Roof area	20,000 ft^2
Roof U-value	0.09 Btu/ft^2.hr.°F
Design room temperature T_{room}	73 °F
Total air flow rate	1 cfm/ft^2
Minimum air flow rate -VAV systems-	0.5 cfm/ft^2
Outside air flow rate	0.15 cfm/ft^2
Economizer	None
Average internal heat gain Q_{int}	1.4 W/ft^2
Solar gains in Btu/hr/ft^2 of building floor area (linear between defined points)	◆ Pasadena: 0.77 at T_{OA-min}=32 °F 0.98 at T_{OA-max}=97 °F ◆ Sacramento: 0.49 at T_{OA-min}=27 °F 1.27 at T_{OA-max}=107 °F ◆ Oakland: 0.54 at T_{OA-min}=32 °F 1.08 at T_{OA-max}=82 °F
Air infiltration	None – building positively pressurized
Average occupancy	200 ft^2/person
Return air and room air temperature difference	2 °F
Cold deck temperature T_c	55 °F
Hot deck schedule T_h -DD systems- (linear between defined points and constant outside lower and higher limits)	110 °F at T_{OA}=40 °F 80 °F at T_{OA}=70 °F 70 °F at T_{OA}=100 °F
Preheat location	Outside air
Preheat temperature T_{ph} schedule	45 °F for T_{OA}<45 °F

The AirModel simulation program approximates solar gains as a linear function of outside air temperature as recommended by Knebel (1983). Required inputs of winter and summer average solar gains for the three cities were calculated using the Klein-Theilacker method (Duffie and Beckman, 1991).

The characteristic signatures were generated by running the baseline simulation with a selected weather file, then altering key calibration parameters one by one and calculating the impact on total cooling and heating energy consumption. Table A-3 shows the alterations of the key calibration parameters used to generate the characteristic signatures for the four AHU types. These calibration parameters have a significant influence on energy consumption, are perceived as having a significant influence (and thus are commonly considered for making calibration changes) or are those in which the authors have frequently seen errors.

Table A-3. Alterations of calibration parameters used to generate characteristic signatures for the four AHU types

Calibration parameter	Baseline	Alteration			
		SDVAV	SDCV	DDVAV	DDCV
Cold deck temperature T_c (°F)	55	54	54	53	52
Hot deck temperature T_h (°F) vs. outdoor temperature T_{OA}: ◆ At T_{OA}= 40 °F ◆ At T_{OA}= 70 °F ◆ At T_{OA}= 100 °F	110 80 70			Increased by 3 °F	Increased by 2 °F
Minimum air flow rate (cfm/ft^2)	0.5	0.47		0.40	
Supply air flow rate (cfm/ft^2)	1		1.08		1.08
Conditioned floor area (ft^2)	120,000	130,000			
Pre-heat temperature T_{ph} (°F)	45	55			
Internal gains Q_{int} (W/ft^2)	1.4	1.2	1	1.2	1
Outside air flow rate (cfm/ft^2)	0.15	0.20			
Room Temperature T_{room} (°F)	73	74	74	73	74
Envelope U-value (Btu/ft^2.hr.°F) ◆ Window ◆ Exterior wall ◆ Roof	0.7 0.1 0.09	Decreased by 15%	Decreased by 20%	Decreased by 15%	Decreased by 20%
Economizer	None	Temperature economizer at [40,58°F]			

APPENDIX B: DESCRIPTION OF BUILDING AND SYSTEM MODEL USED IN ILLUSTRATIVE EXAMPLES

The two illustrative examples use the same prototypical 6-floor office building shown in Figure A-7. The HVAC system used is the DDCV system shown in Figure A-2 with the operational equations shown in Figure A-5. The two examples were simulated with AirModel using Pasadena weather data. Table B-1 shows key characteristics of the building and system model.

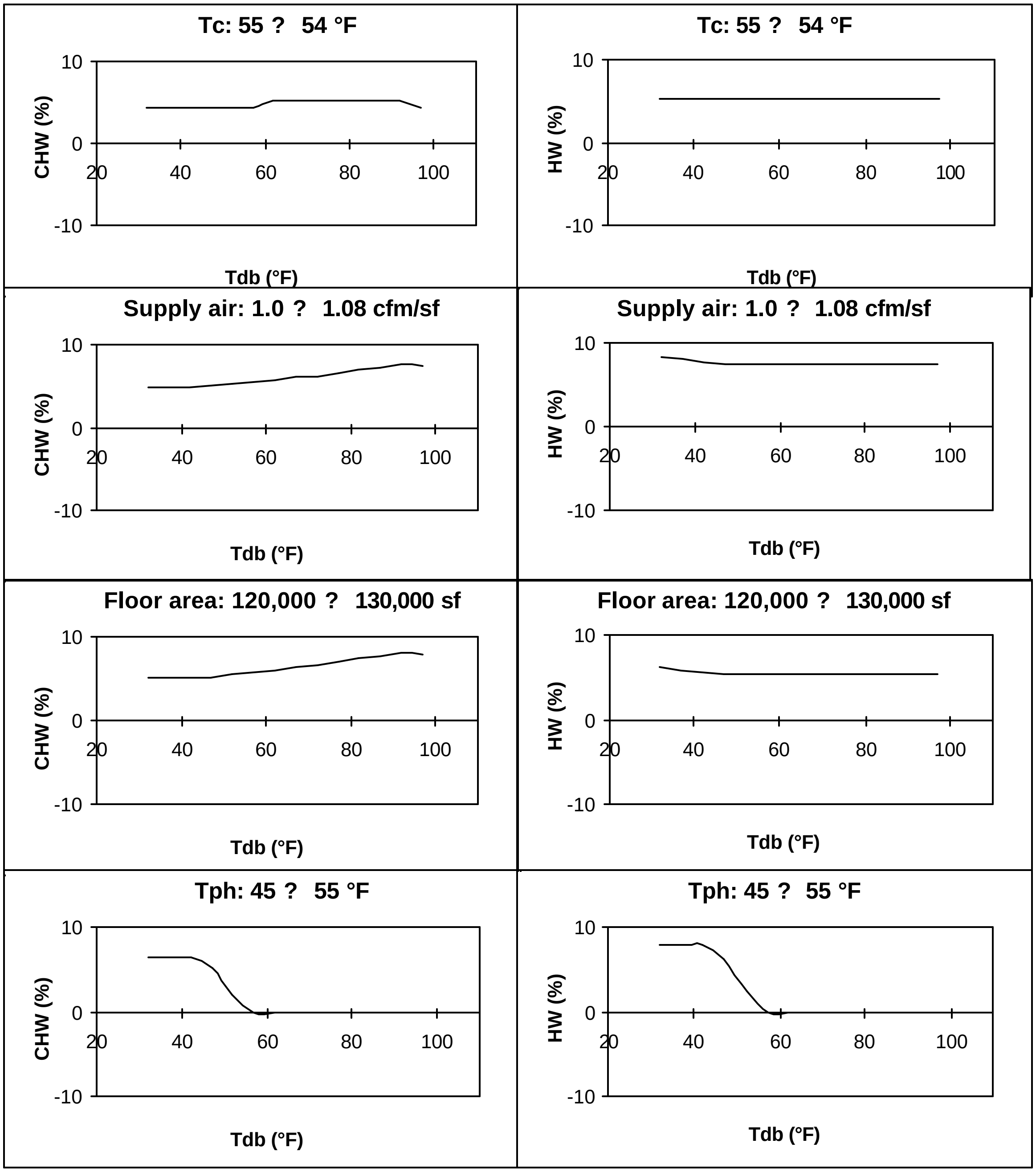
Table B-1. Key building and system characteristics of the building used in the illustrative examples

Parameter	Value
Conditioned floor area	120,000 ft^2
Interior zone ratio	0.5
Exterior wall area	37,800 ft^2
Exterior wall U-value	0.1 $Btu/ft^2.hr.°F$
Window area	16,200 ft^2
Window U-value	0.7 $Btu/ft^2.hr.°F$
Roof area	20,000 ft^2
Roof U-value	0.09 $Btu/ft^2.hr.°F$
Design room temperature T_{room}	73 °F
Maximum room relative humidity	50 %
Total air flow rate	1.2 cfm/ft^2
Outside air flow rate	0.1 cfm/ft^2
Economizer	None
Average internal heat gain Q_{int}	0.8 W/ft^2
Solar gains in $Btu/hr/ft^2$ of building floor area	0.77 at T_{OA-min}=32 °F 0.98 at T_{OA-max}=97 °F
Air infiltration	None
Average occupancy	200 ft^2/person
Difference between return and room air temperatures	2 °F
Cold deck temperature T_c	55 °F
Hot deck schedule T_h (linear between defined points and constant outside lower and higher limits)	110 °F at T_{OA}=40 °F 80 °F at T_{OA}=70 °F 70 °F at T_{OA}=100 °F
Preheat location	Outside air
Preheat schedule T_{ph}	45 °F for T_{OA}<45 °F

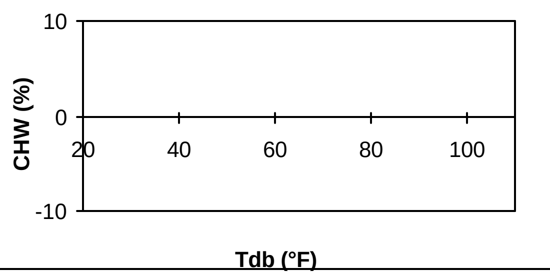
The solar gains were calculated using the Klein-Theilacker method (Duffie and Beckman, 1991).

APPENDIX C: CHARACTERISTIC SIGNATURES FOR SDCV SYSTEMS

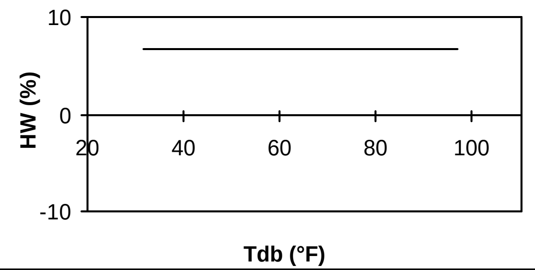
APPENDIX C-1: SDCV SYSTEM IN PASADENA



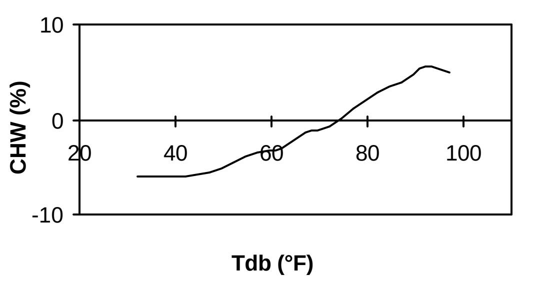
Qint: 1.4 ? 1 W/sf



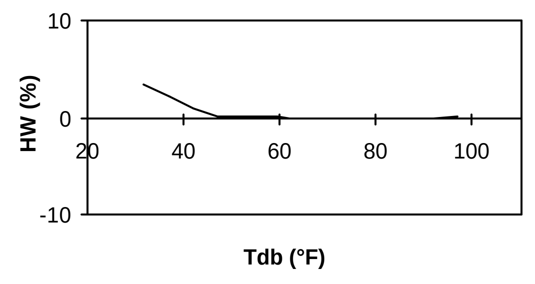
Qint: 1.4 ? 1 W/sf



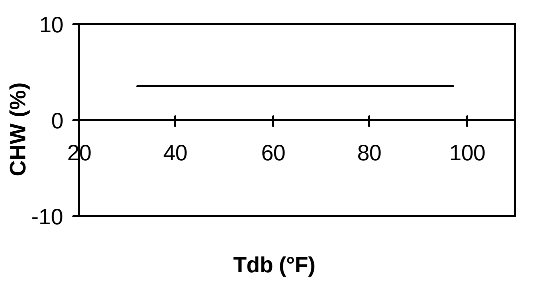
Outside air: 0.15 ? 0.20 cfm/sf



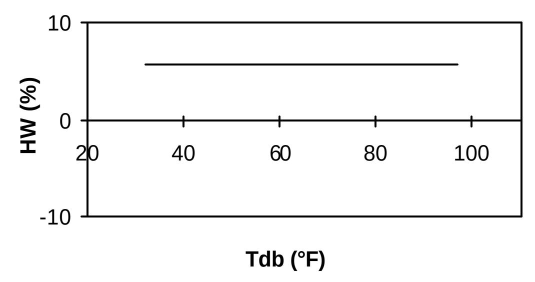
Outside air: 0.15 ? 0.20 cfm/sf



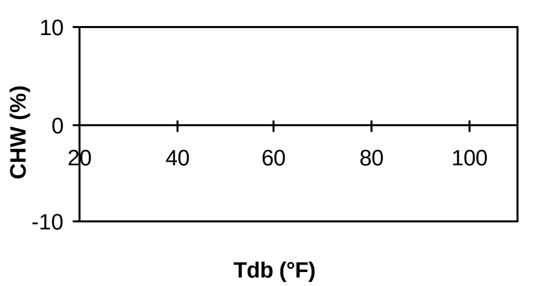
Troom: 73 ? 74 °F



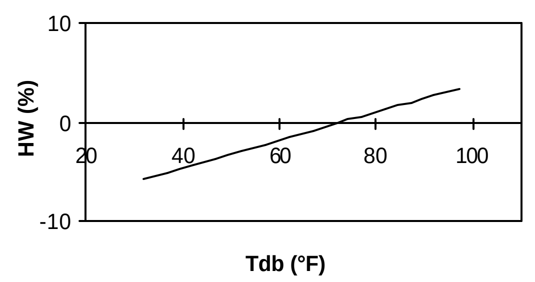
Troom: 73 ? 74 °F



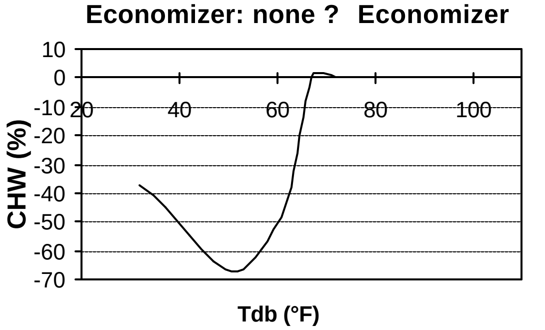
Envelope U value decreased by 20%



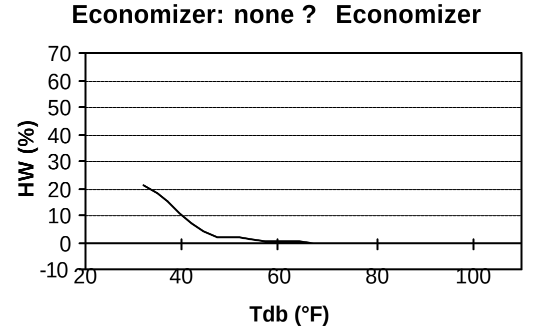
Envelope U value decreased by 20%



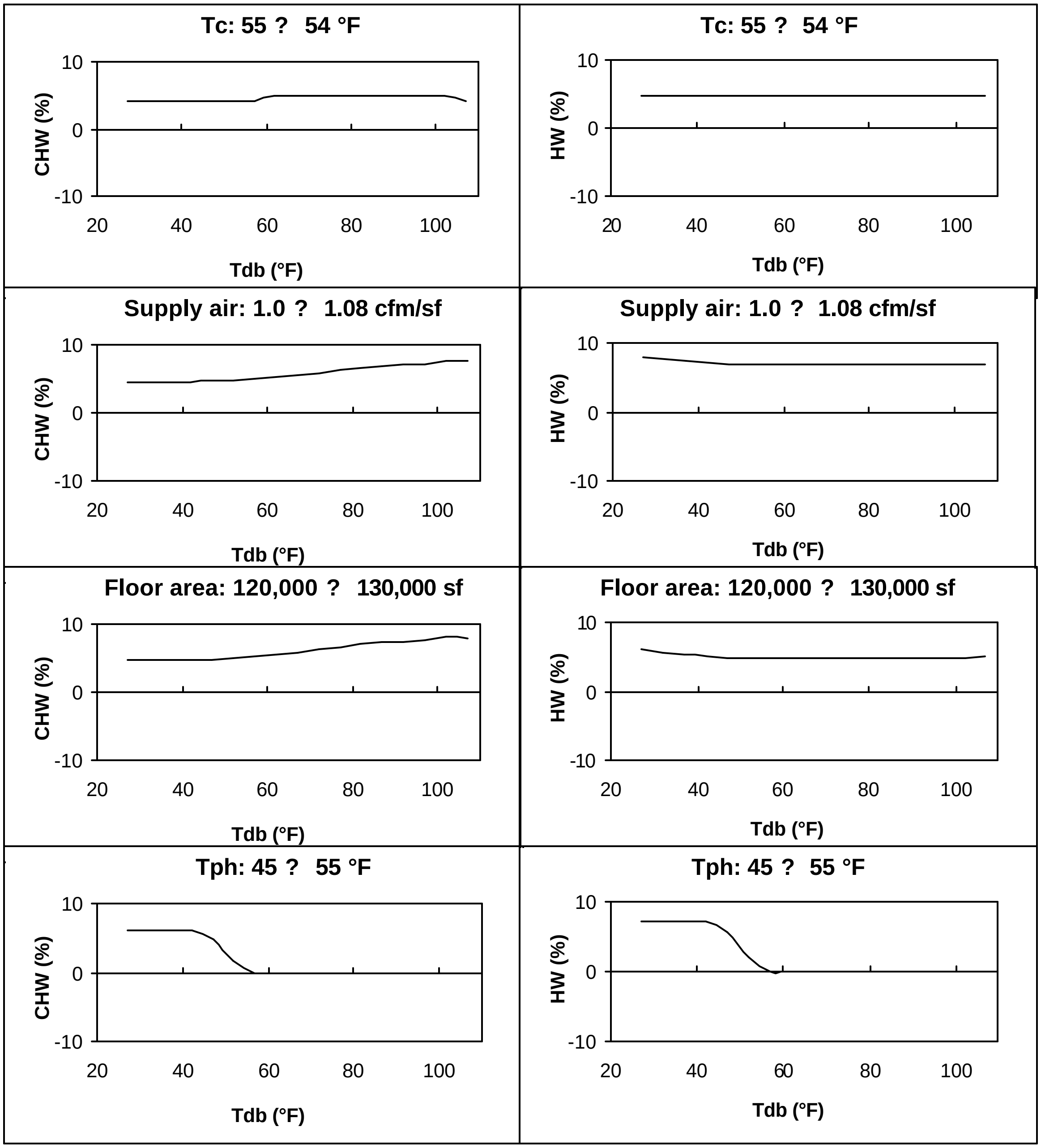
Economizer: none ? Economizer

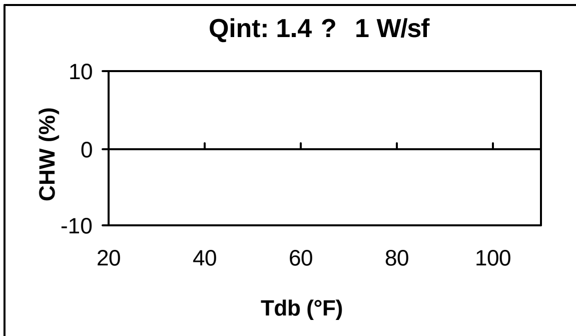


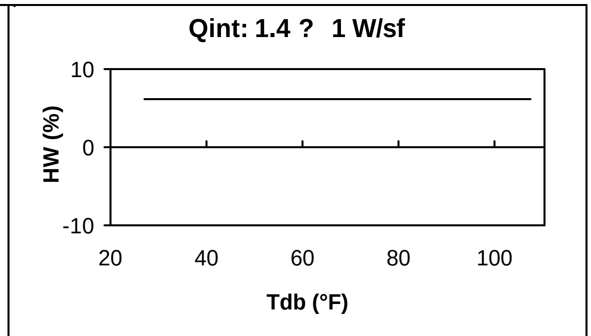
Economizer: none ? Economizer

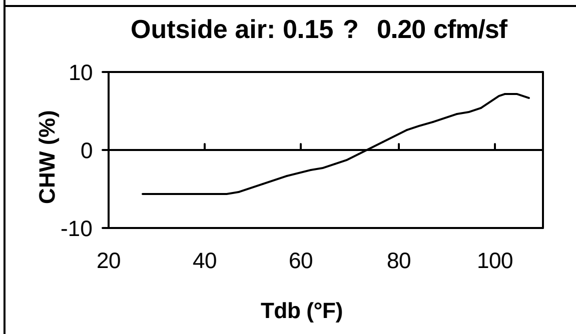


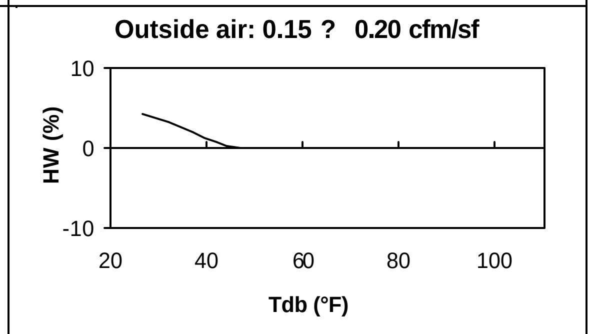
APPENDIX C-2: SDCV SYSTEM IN SACRAMENTO

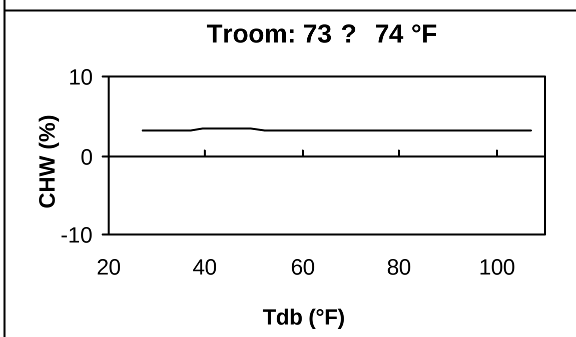


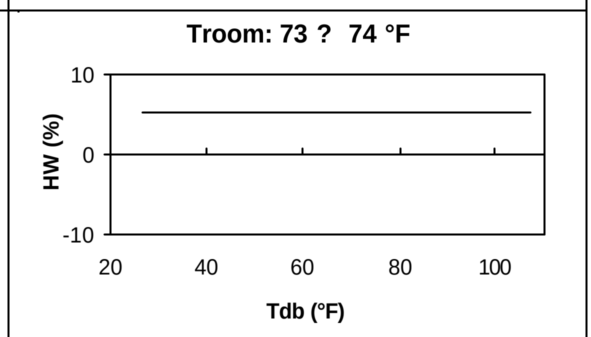

Qint: 1.4 ? 1 W/sf
CHW (%)
10
0
-10
20
40
60
80
100
Tdb (°F)

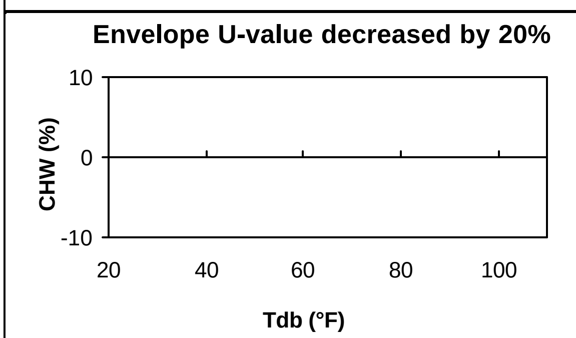

Qint: 1.4 ? 1 W/sf
HW (%)
10
0
-10
20
40
60
80
100
Tdb (°F)


Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
10
0
-10
20
40
60
80
100
Tdb (°F)


Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
10
0
-10
20
40
60
80
100
Tdb (°F)


Troom: 73 ? 74 °F
CHW (%)
10
0
-10
20
40
60
80
100
Tdb (°F)


Troom: 73 ? 74 °F
HW (%)
10
0
-10
20
40
60
80
100
Tdb (°F)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CHW (%)
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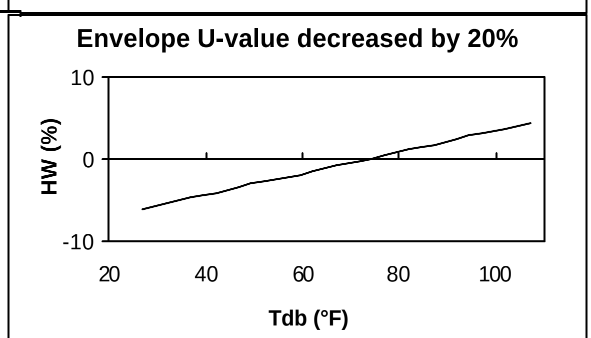
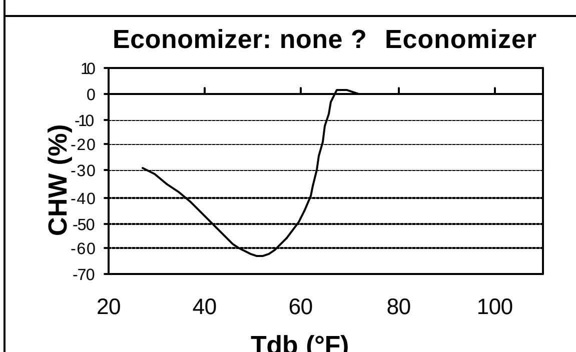
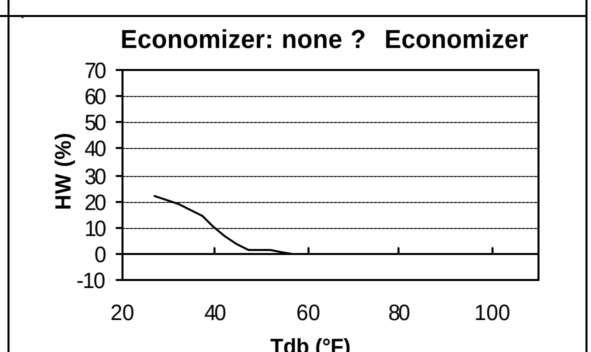
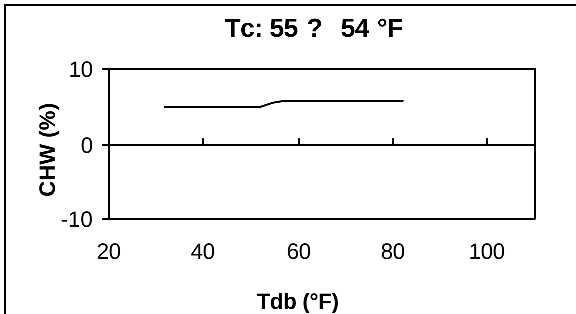
0
-10
20
40
60
80
100
Tdb (°F)

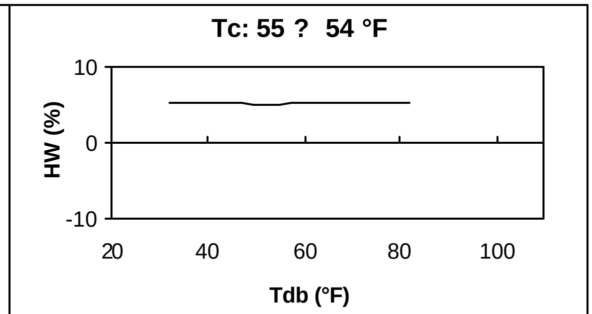

Envelope U-value decreased by 20%
HW (%)
10
0
-10
20
40
60
80
100
Tdb (°F)

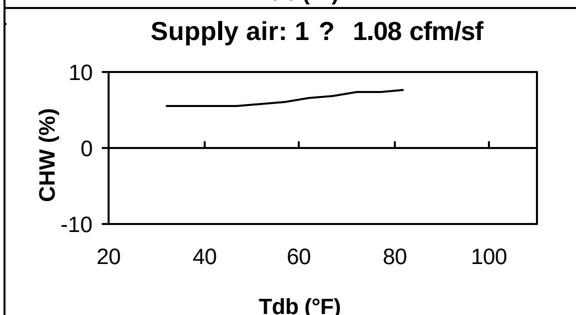

Economizer: none ? Economizer
CHW (%)
10
0
-10
-20
-30
-40
-50
-60
-70
20
40
60
80
100
Tdb (°F)

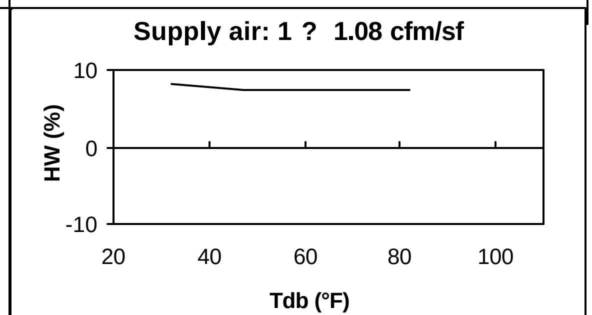

Economizer: none ? Economizer
HW (%)
70
60
50
40
30
20
10
0
-10
20
40
60
80
100
Tdb (°F)

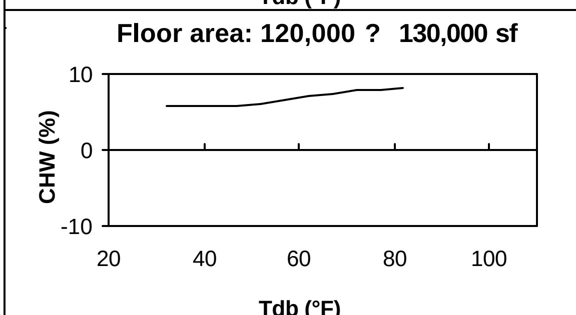
APPENDIX C-3: SDCV SYSTEM IN OAKLAND

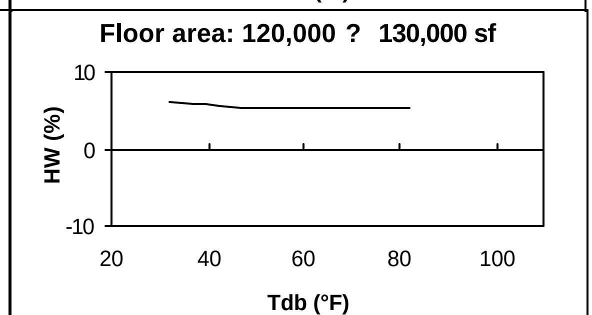


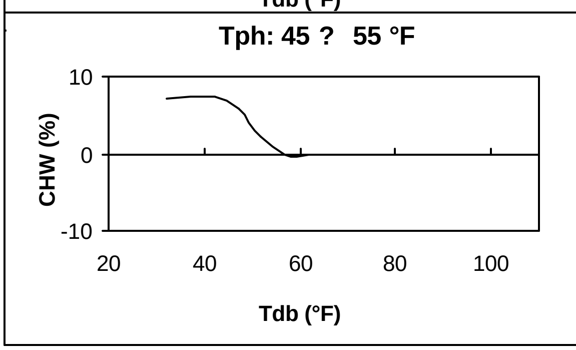


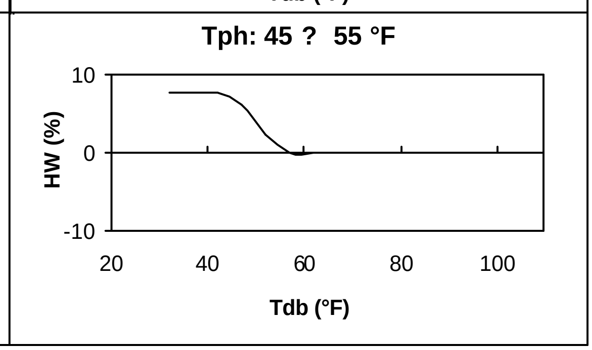




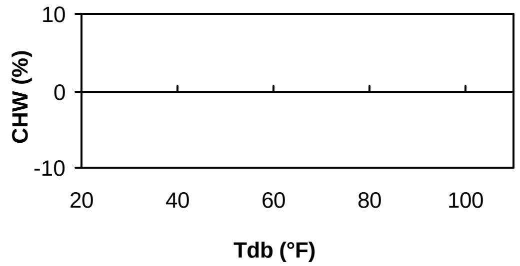




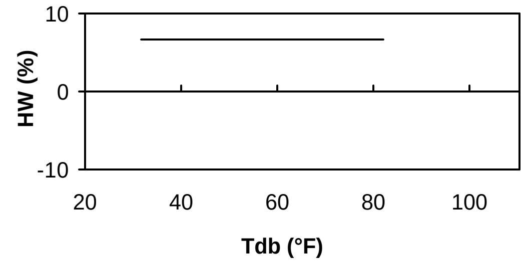




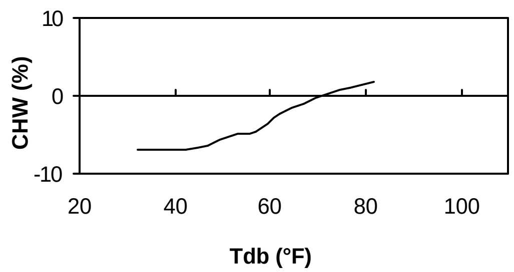
Qint: 1.4 ? 1 W/sf



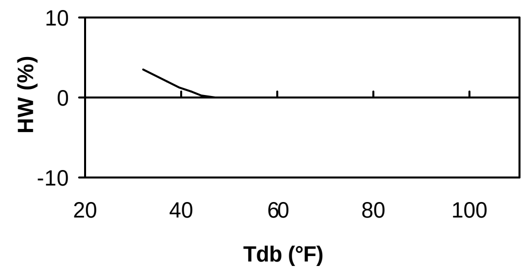
Qint: 1.4 ? 1 W/sf



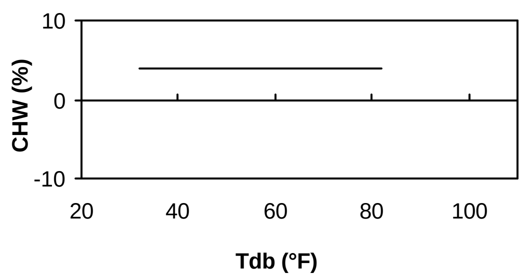
Outside air: 0.15 ? 0.20 cfm/sf



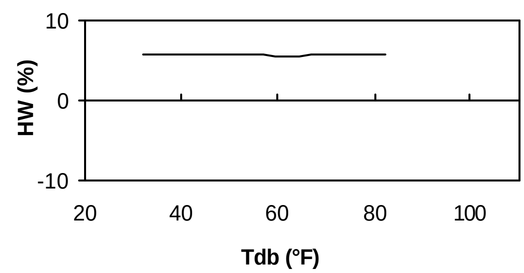
Outside air: 0.15 ? 0.20 cfm/sf



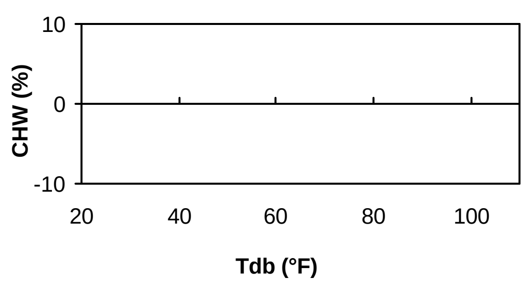
Troom: 73 ? 74 °F



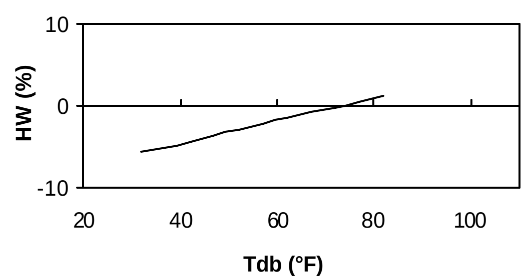
Troom: 73 ? 74 °F



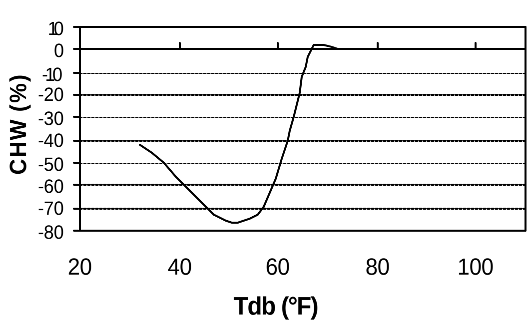
Envelope U-value decreased by 20%



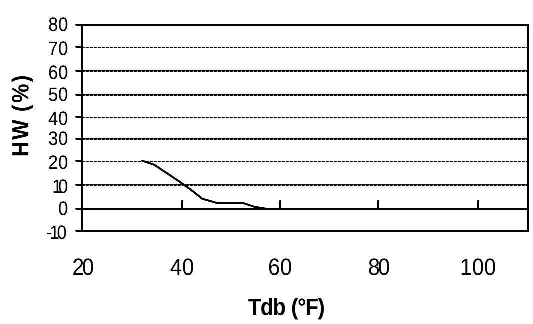
Envelope U-value decreased by 20%



Economizer: none ? Economizer

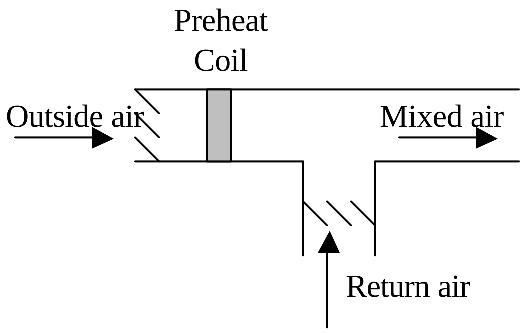


Economizer: none ? Economizer

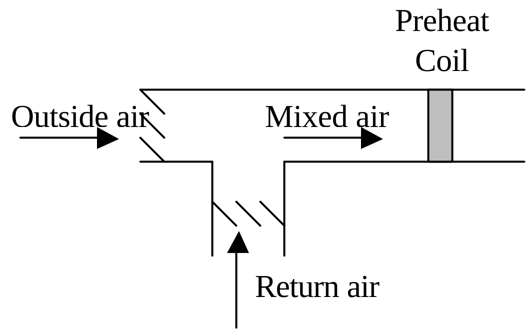


AIR HANDLING UNITS WITH PREHEATING AFTER MIXING

As shown in Figure C-1, the preheat coil can be located in the outside air or the mixed air stream.



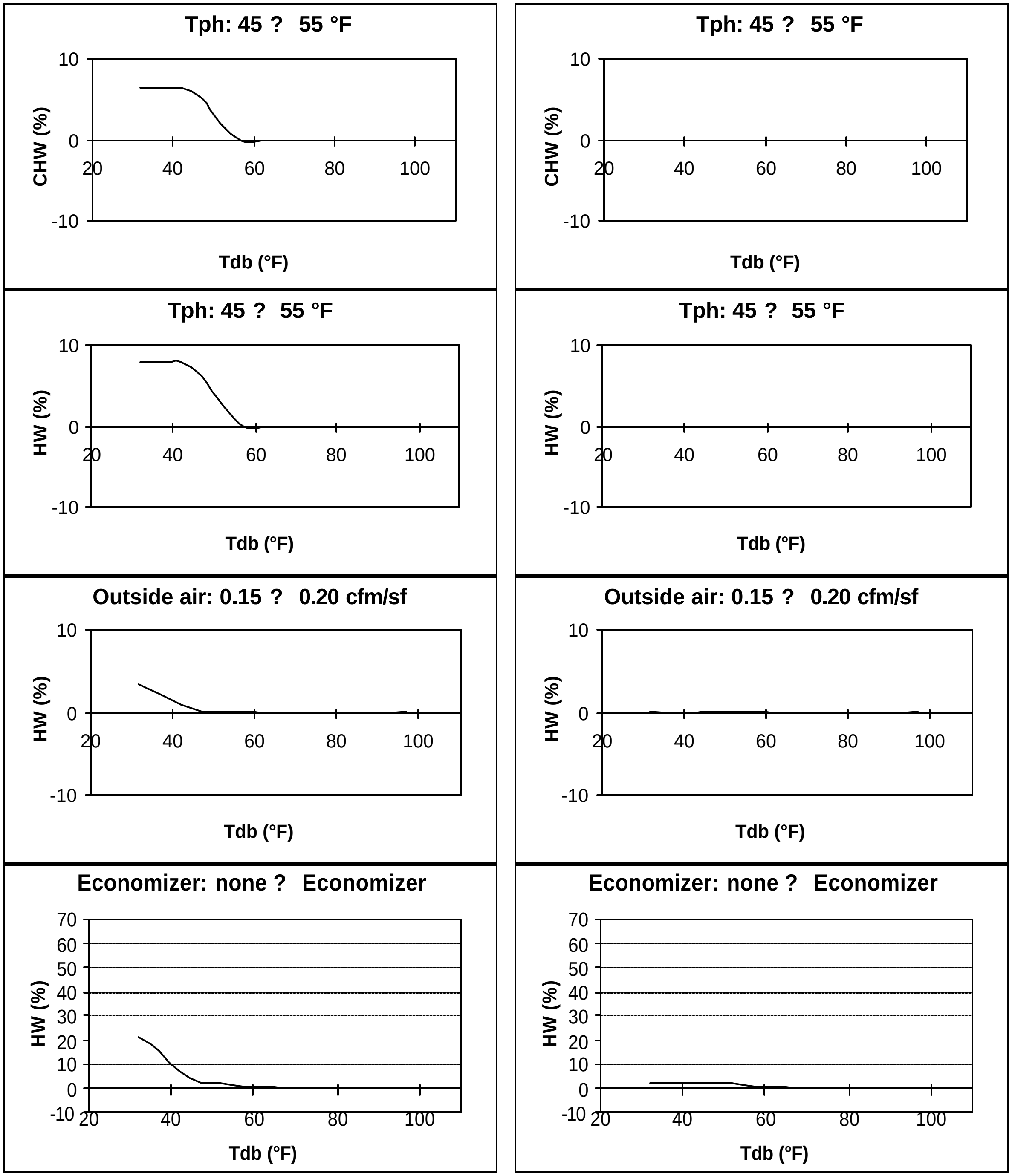
a) Preheat located in outside air stream



b) Preheat located in mixed air stream

Figure C-1. Preheat Locations

Systems used to generate characteristic signatures in this manual have preheating in the outside air stream as shown in Figure C-1a. However, the sets of characteristic signatures provided in this Appendix can be used for systems with preheat in either location. The main differences occur at the lower range of outside air temperatures where the preheating temperature setpoint can be higher than the outside air temperature but lower than the mixed air temperature. Figure C-2 shows the characteristic signatures that differ between a Single Duct Constant Volume system with preheat at the outside air stream and the same system type with preheat at the mixed air stream for Pasadena weather. The other characteristic signatures are similar.



a) SDCV system with preheat at outside air stream

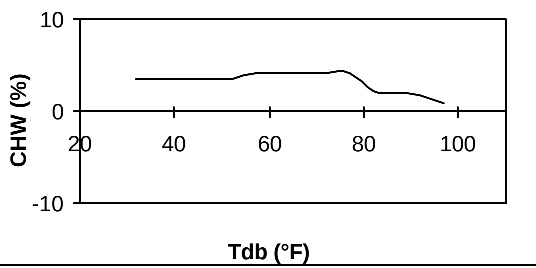
b) SDCV system with preheat at mixed air stream

Figure C-2. Comparison of calibration signatures for different preheat locations

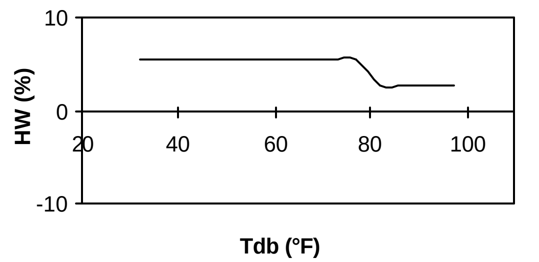
APPENDIX D: CHARACTERISTIC SIGNATURES FOR SDVAV SYSTEMS

APPENDIX D-1: SDVAV SYSTEM IN PASADENA

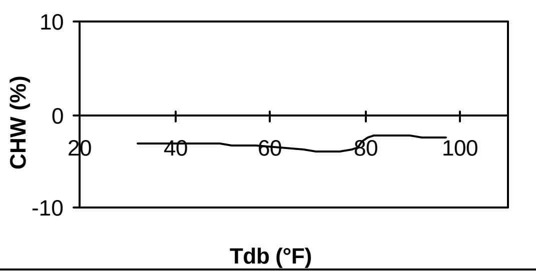
Tc: 55 ? 54 °F



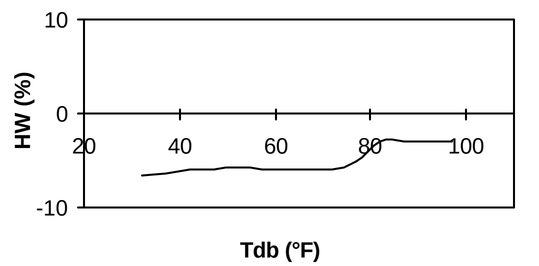
Tc: 55 ? 54 °F



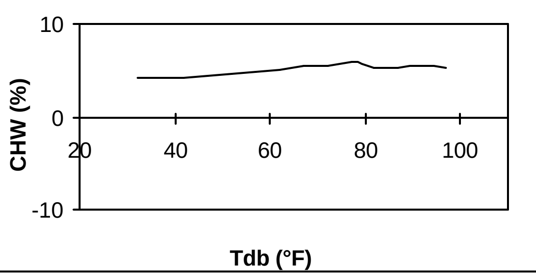
Minimum air flow: 0.5 ? 0.47 cfm/sf



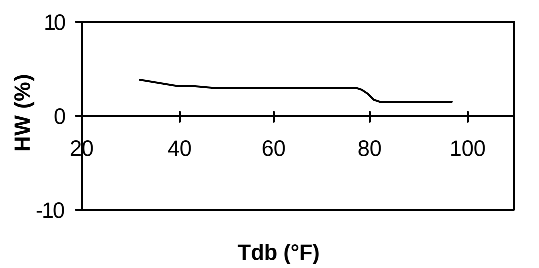
Minimum air flow: 0.5 ? 0.47 cfm/sf



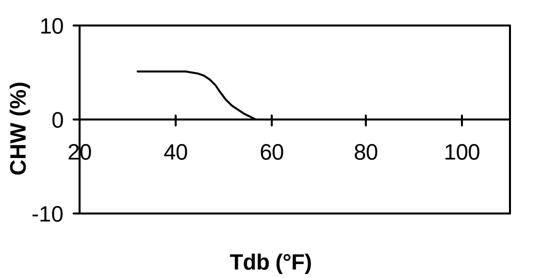
Floor area: 120,000 ? 130,000 sf



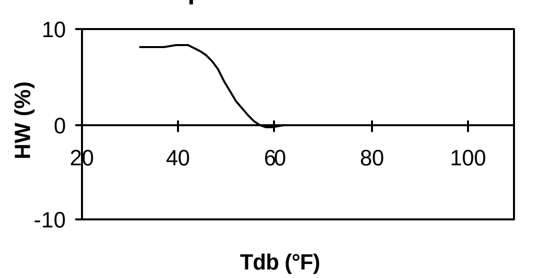
Floor area: 120,000 ? 130,000 sf



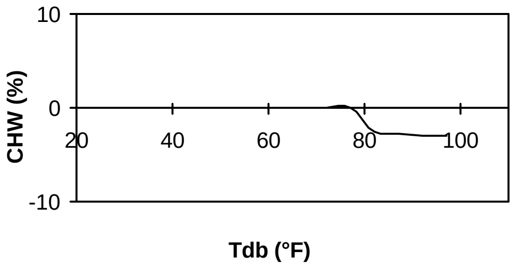
Tph: 45 ? 55 °F



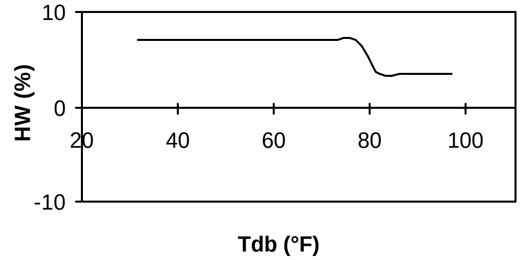
Tph: 45 ? 55 °F



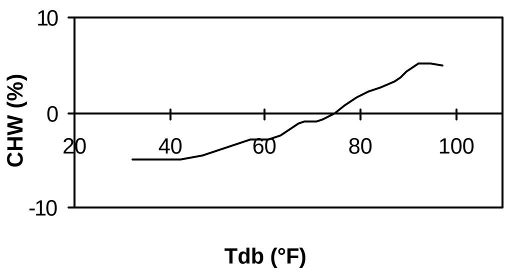
Qint: 1.4 ? 1.2 W/sf



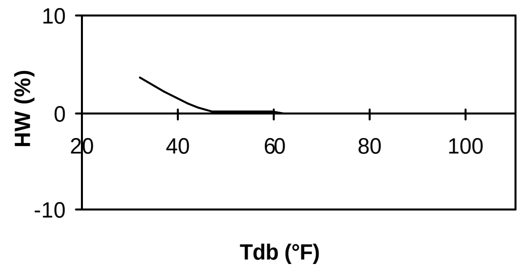
Qint: 1.4 ? 1.2 W/sf



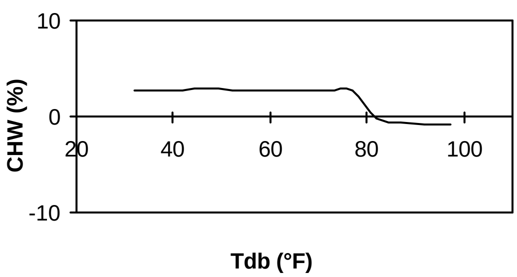
Outside air: 0.15 ? 0.20 cfm/sf



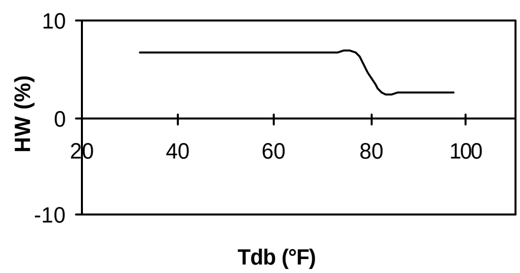
Outside air: 0.15 ? 0.20 cfm/sf



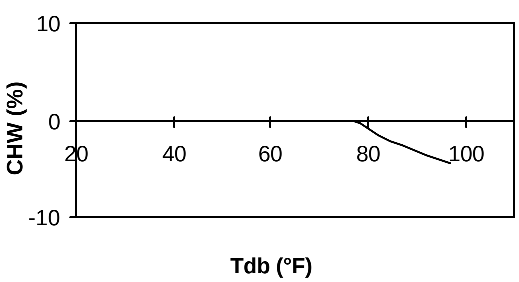
Troom: 73 ? 74 °F



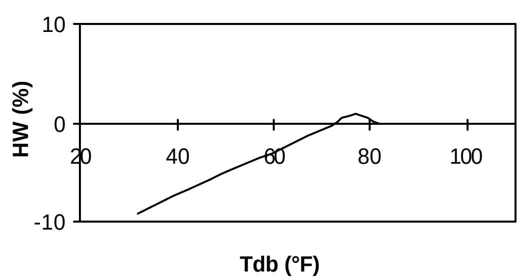
Troom: 73 ? 74 °F



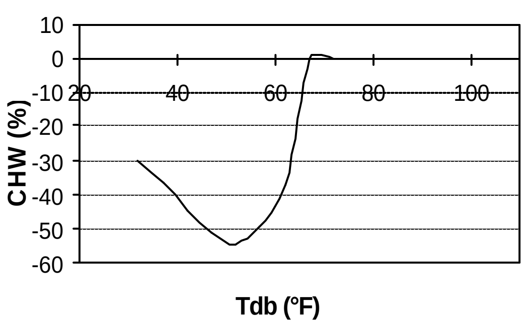
Envelope U-value decreased by 15%



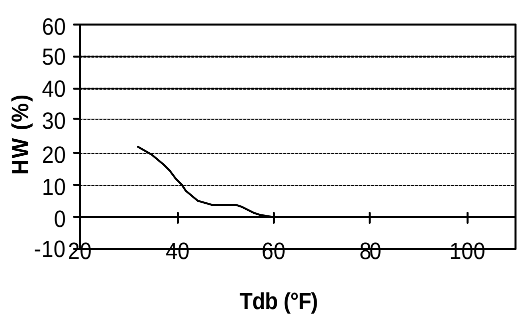
Envelope U-value decreased by 15%



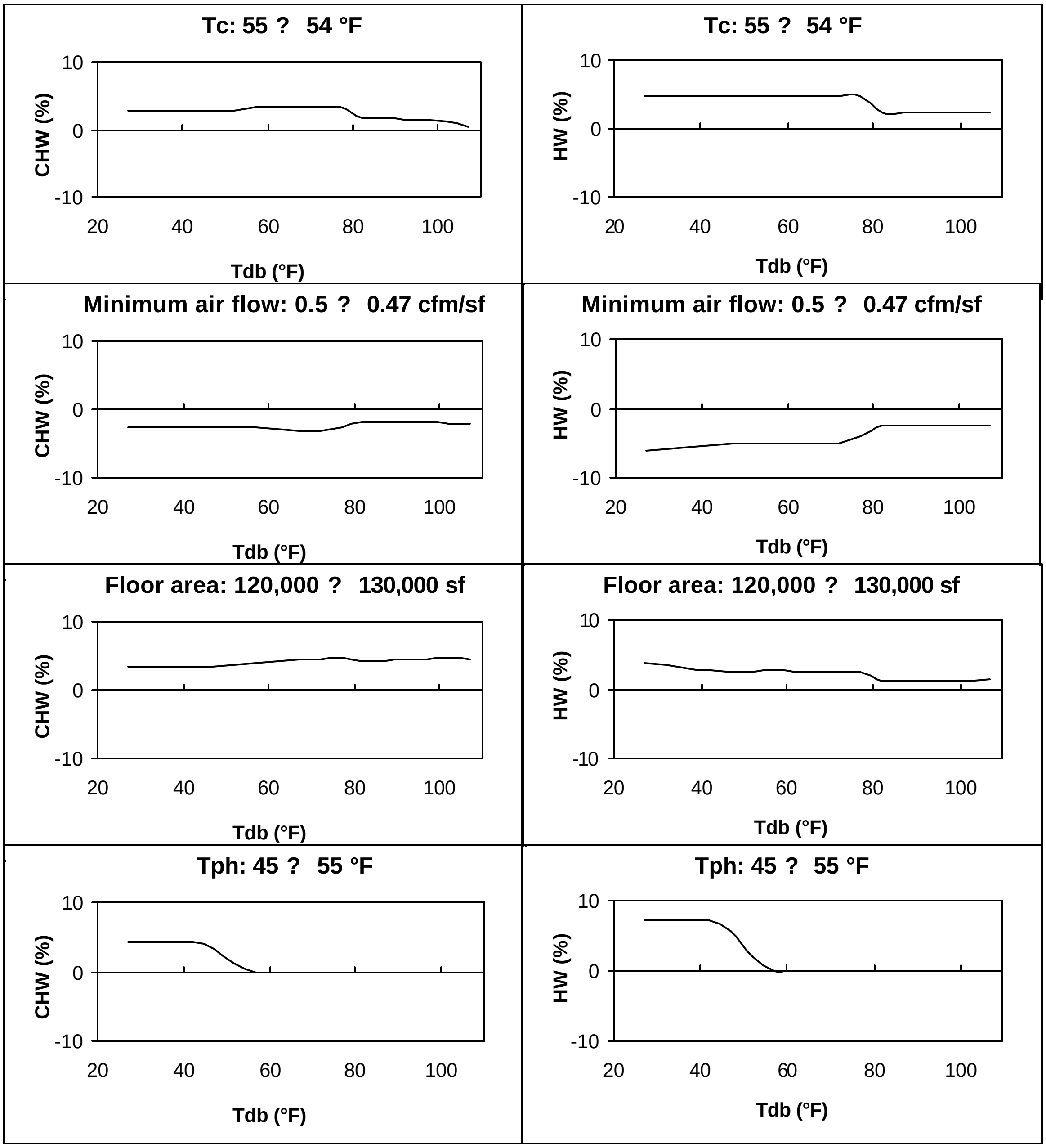
Economizer: none ? Economizer



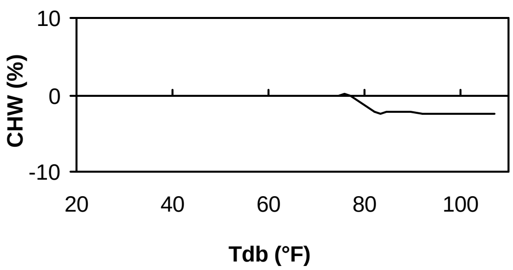
Economizer: none ? Economizer



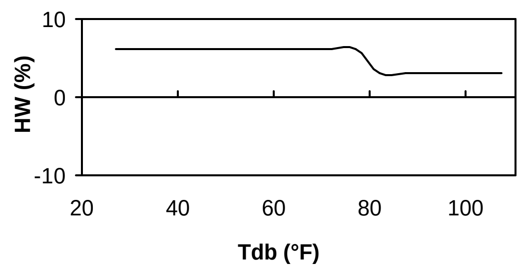
APPENDIX D-2: SDVAV SYSTEM IN SACRAMENTO



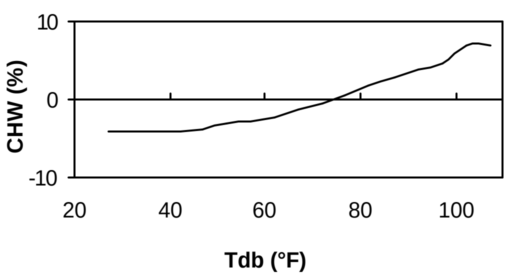
Qint: 1.4 ? 1.2 W/sf



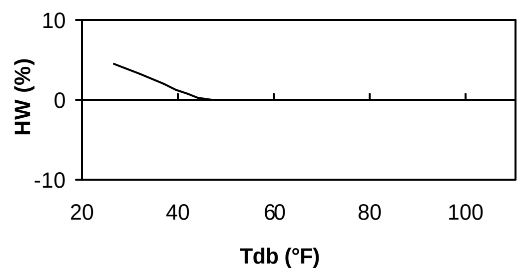
Qint: 1.4 ? 1.2 W/sf



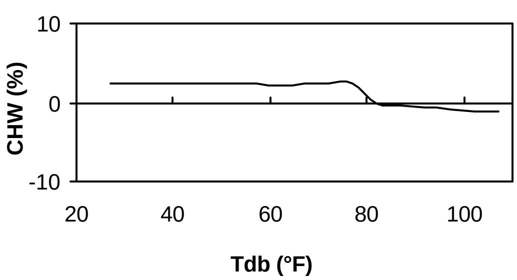
Outside air: 0.15 ? 0.20 cfm/sf



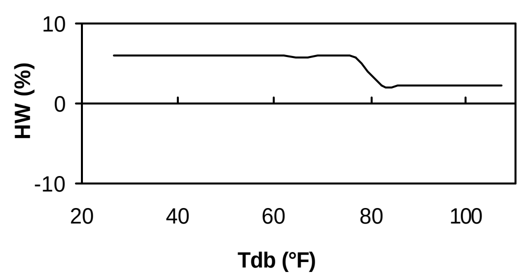
Outside air: 0.15 ? 0.20 cfm/sf



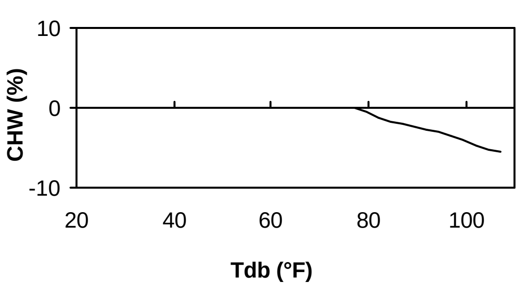
Troom: 73 ? 74 °F



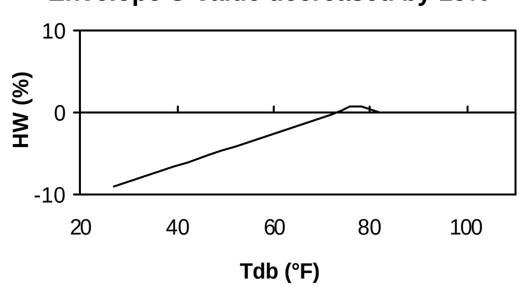
Troom: 73 ? 74 °F



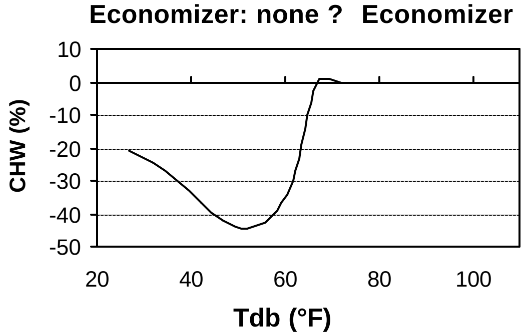
Envelope U-value decreased by 15%



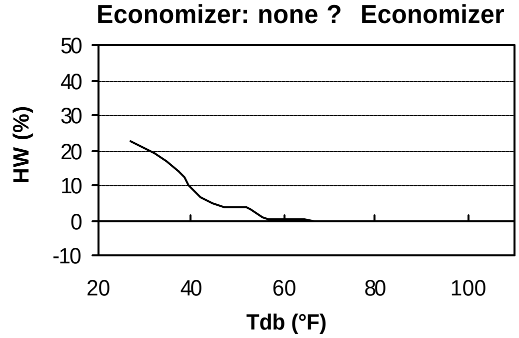
Envelope U-value decreased by 15%



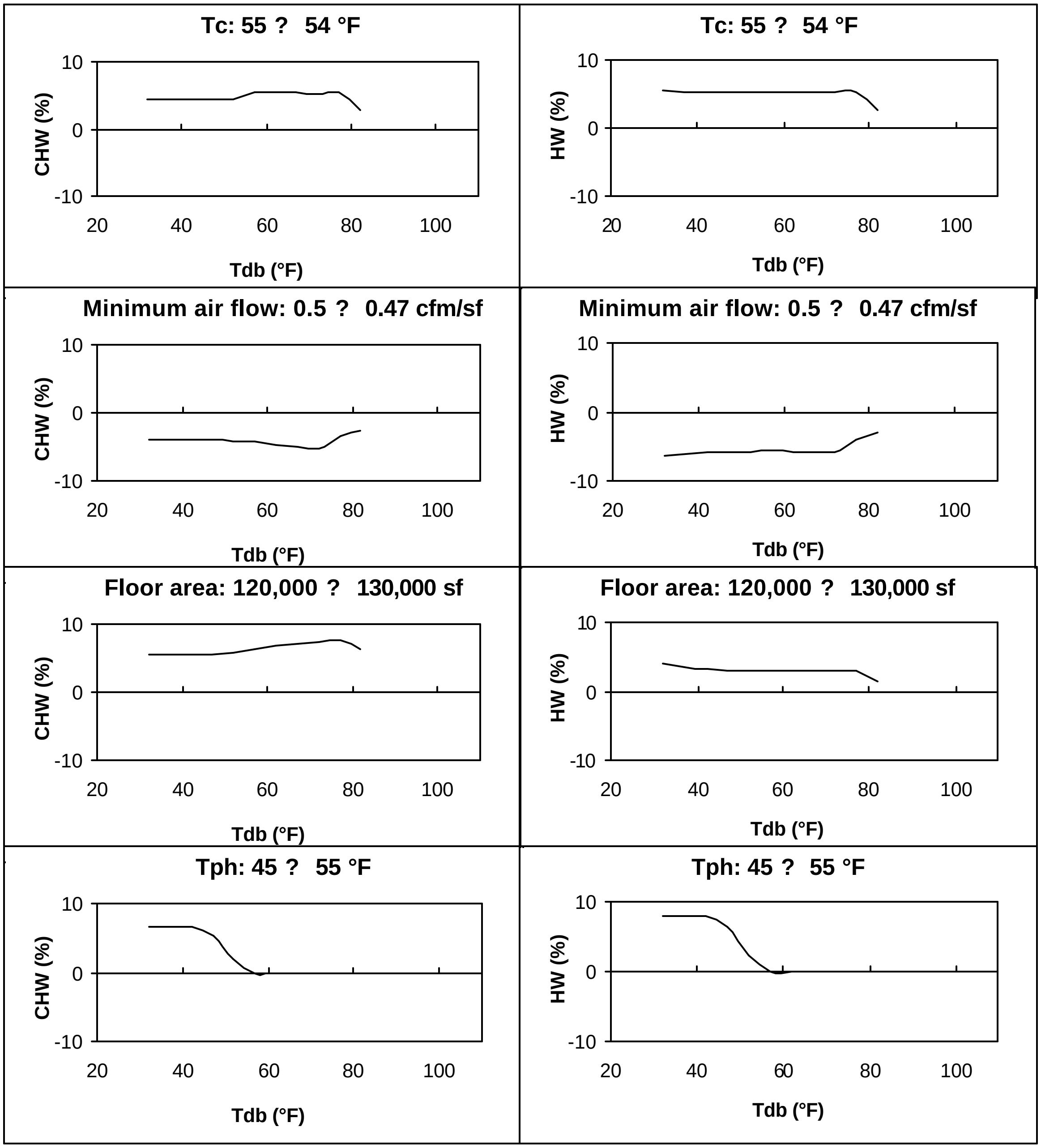
Economizer: none ? Economizer

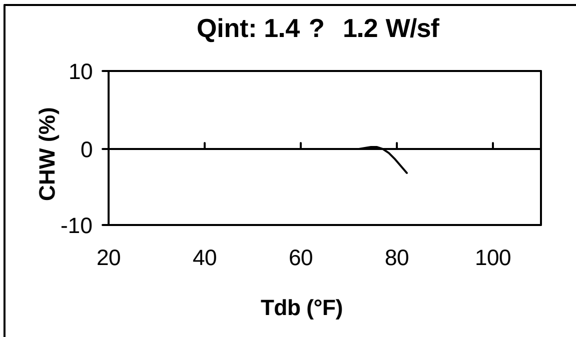


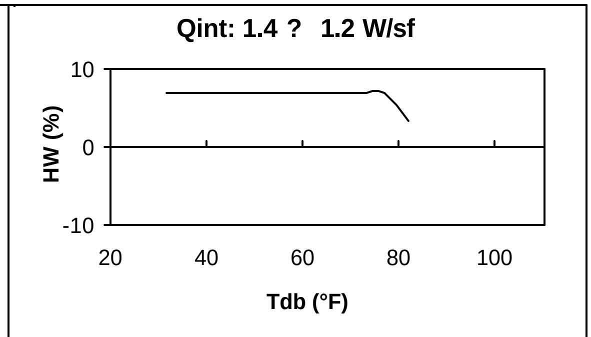
Economizer: none ? Economizer

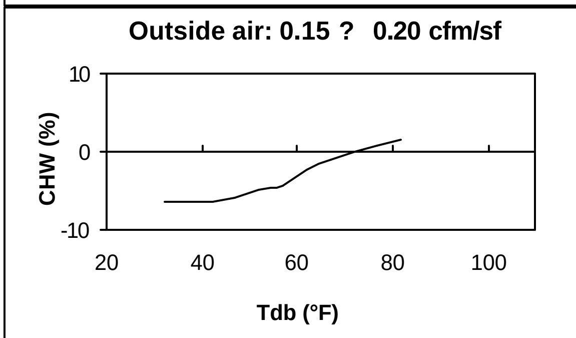


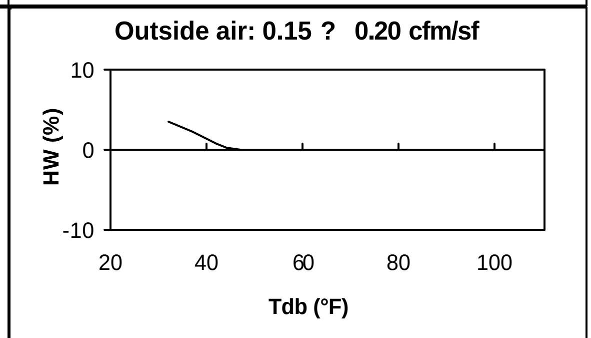
APPENDIX D-3: SDVAV SYSTEM IN OAKLAND

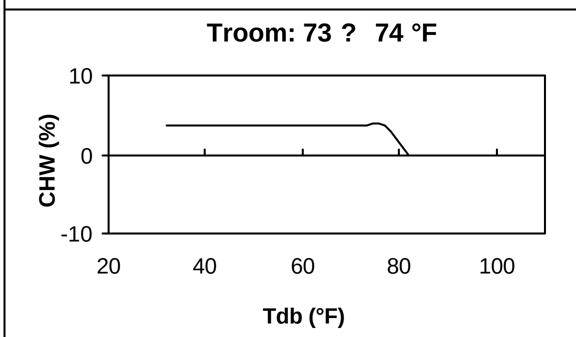


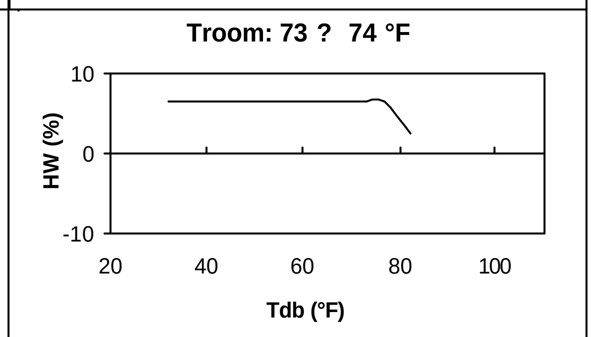

Qint: 1.4 ? 1.2 W/sf
CHW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)

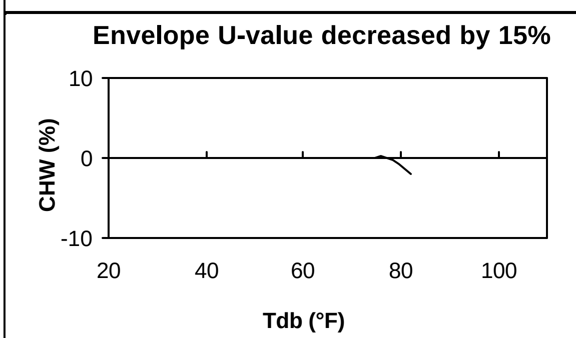

Qint: 1.4 ? 1.2 W/sf
HW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)

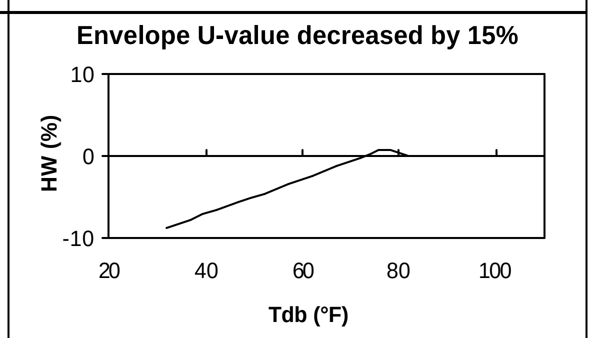

Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)

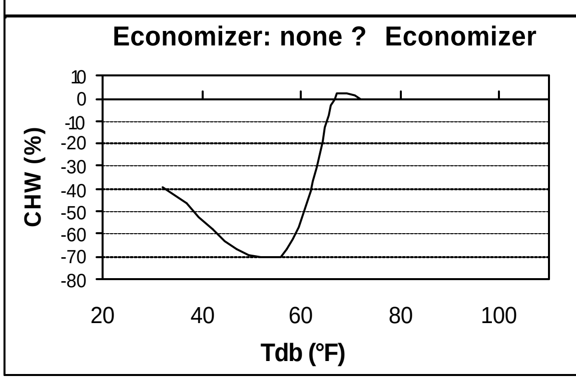

Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)

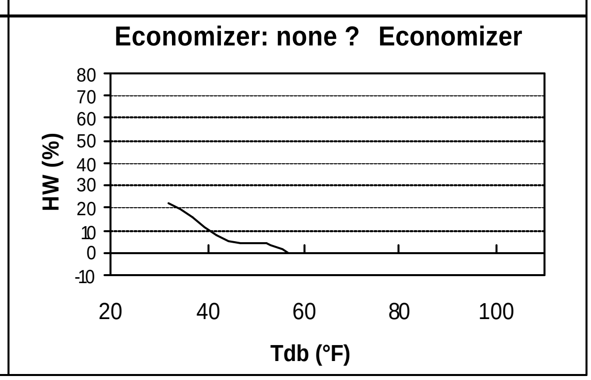

Troom: 73 ? 74 °F
CHW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)


Troom: 73 ? 74 °F
HW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)


Envelope U-value decreased by 15%
CHW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)

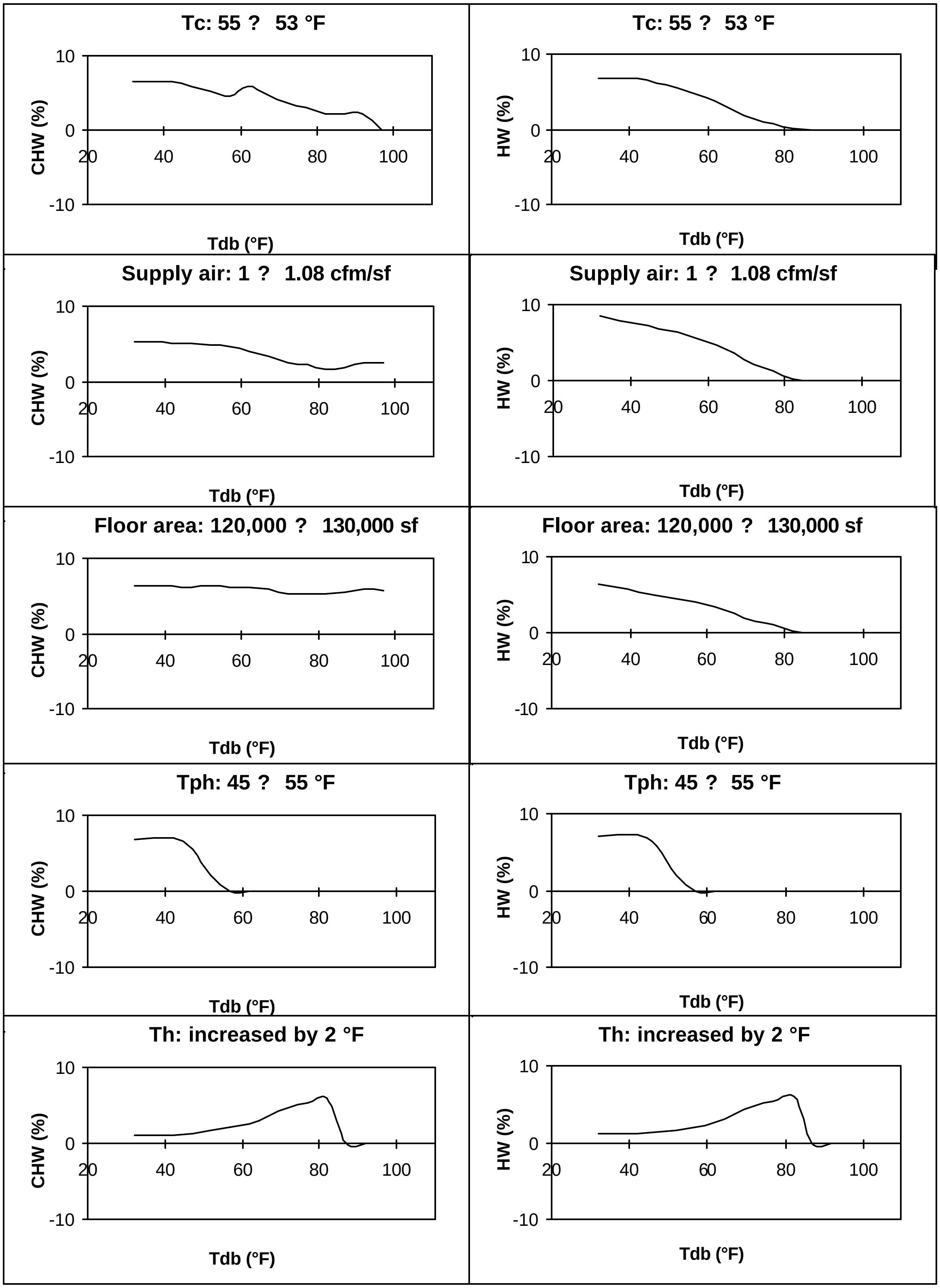

Envelope U-value decreased by 15%
HW (%)
10
0
-10
20 40 60 80 100
Tdb (°F)

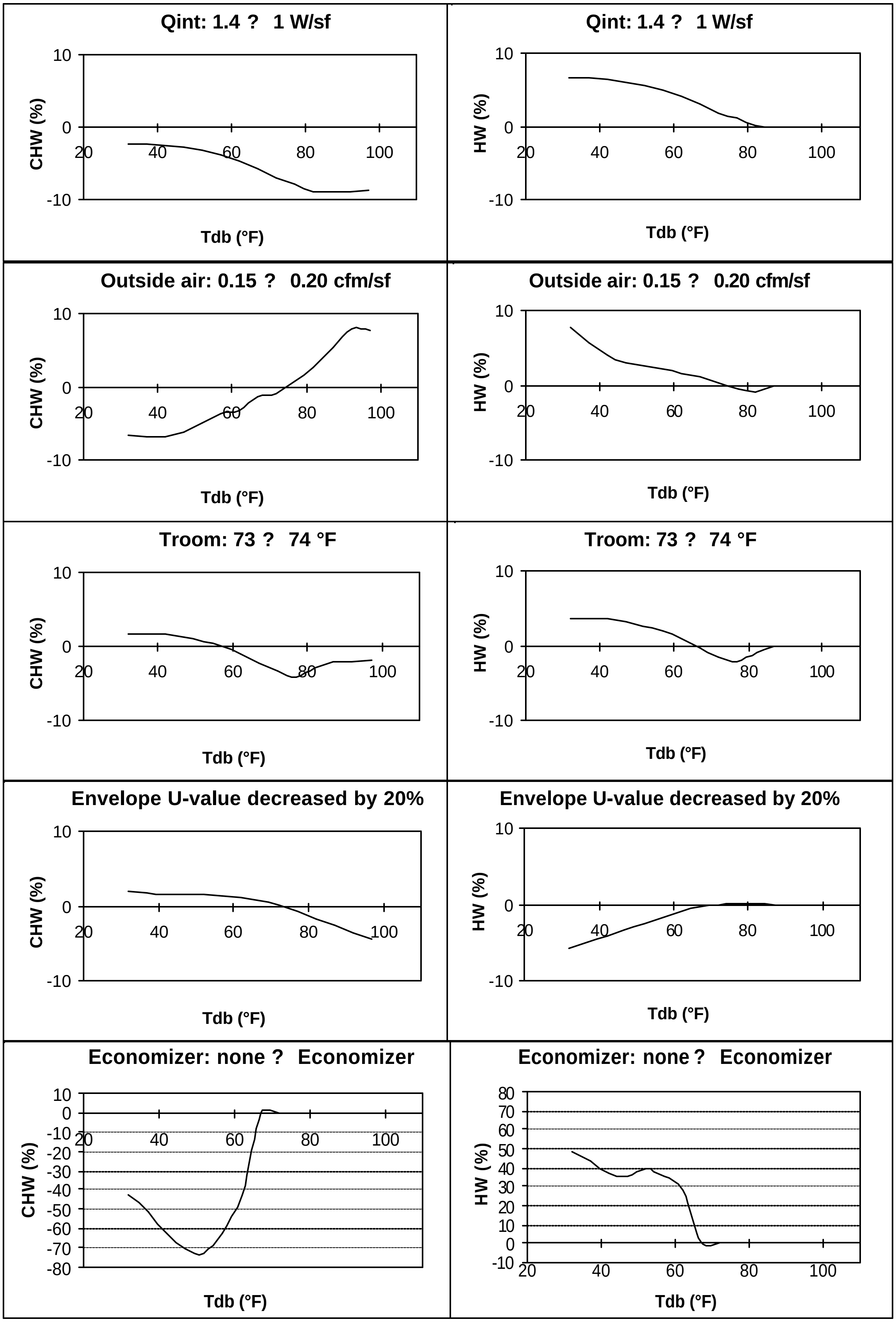

Economizer: none ? Economizer
CHW (%)
10
0
-10
-20
-30
-40
-50
-60
-70
-80
20 40 60 80 100
Tdb (°F)


Economizer: none ? Economizer
HW (%)
80
70
60
50
40
30
20
10
0
-10
20 40 60 80 100
Tdb (°F)

APPENDIX E: CHARACTERISTIC SIGNATURES FOR DDCV SYSTEMS

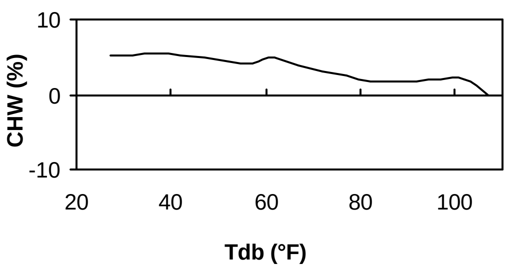
APPENDIX E-1: DDCV SYSTEM IN PASADENA



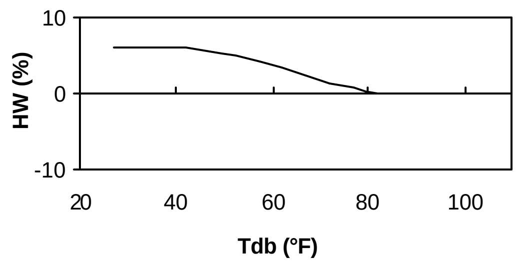

Qint: 1.4 ? 1 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 20%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 20%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

APPENDIX E-2: DDCV SYSTEM IN SACRAMENTO

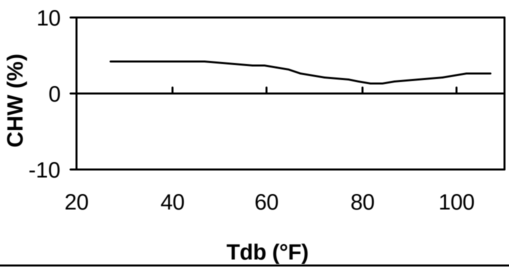
Tc: 55 ? 53 °F



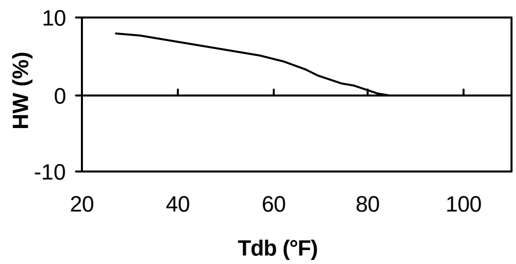
Tc: 55 ? 53 °F



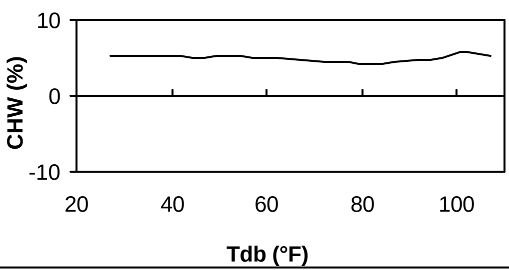
Supply air: 1.0 ? 1.08 cfm/sf



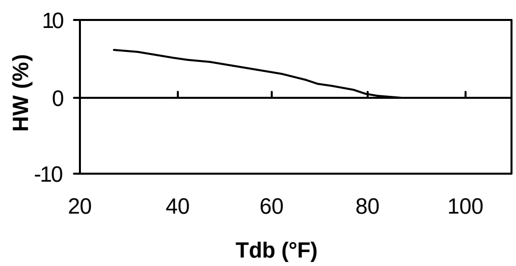
Supply air: 1.0 ? 1.08 cfm/sf



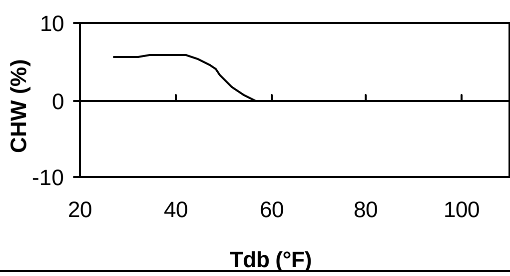
Floor area: 120,000 ? 130,000 sf



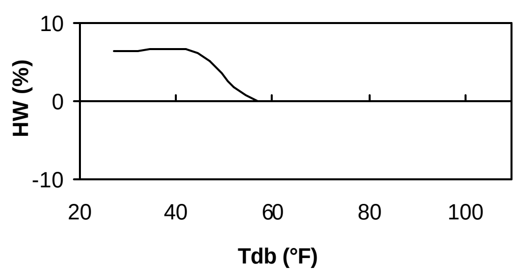
Floor area: 120,000 ? 130,000 sf



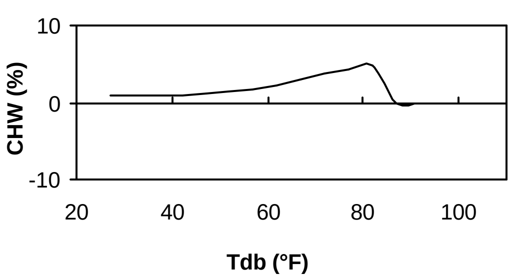
Tph: 45 ? 55 °F



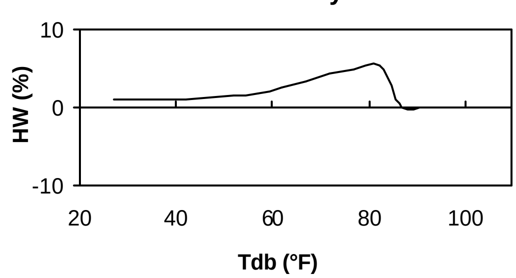
Tph: 45 ? 55 °F



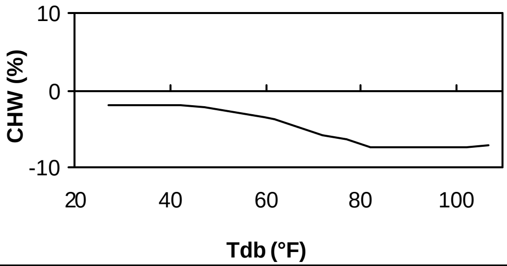
Th: increased by 2 °F



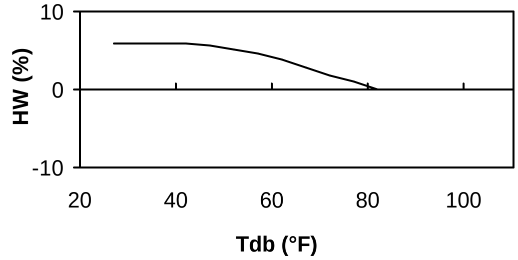
Th: increased by 2 °F



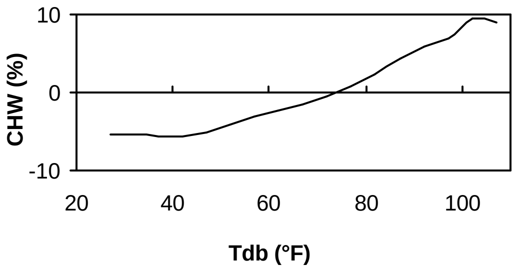
Qint: 1.4 ? 1 W/sf



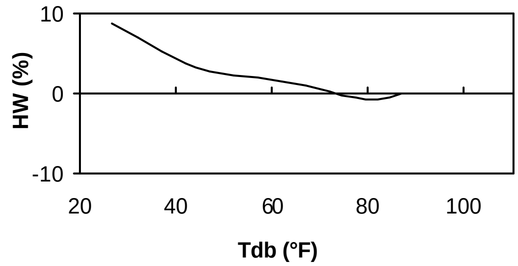
Qint: 1.4 ? 1 W/sf



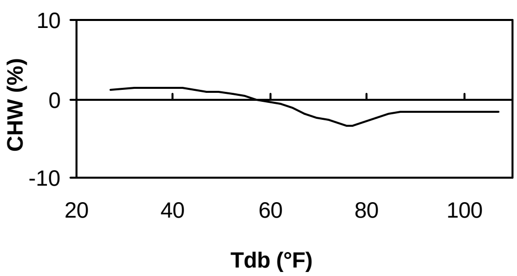
Outside air: 0.15 ? 0.20 cfm/sf



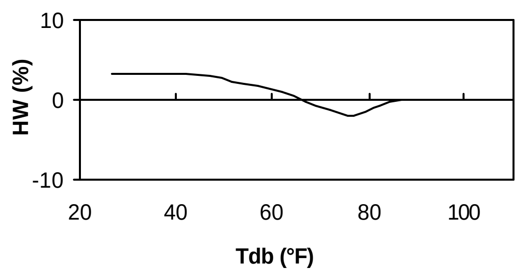
Outside air: 0.15 ? 0.20 cfm/sf



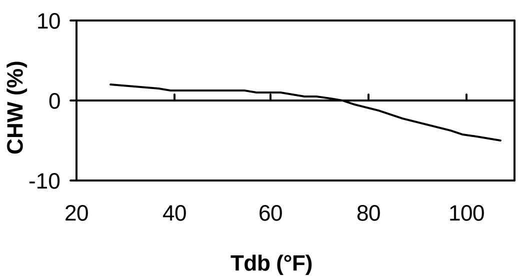
Troom: 73 ? 74 °F



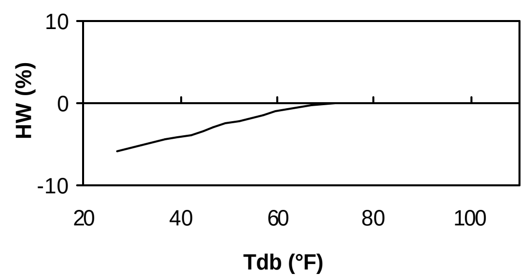
Troom: 73 ? 74 °F



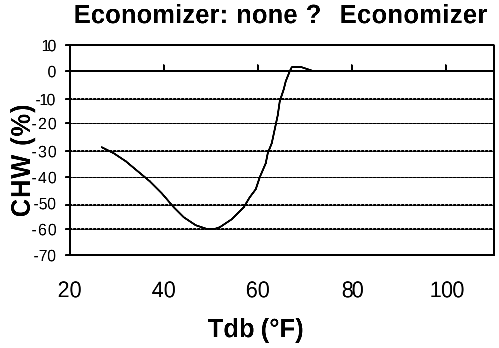
Envelope U-value decreased by 20%



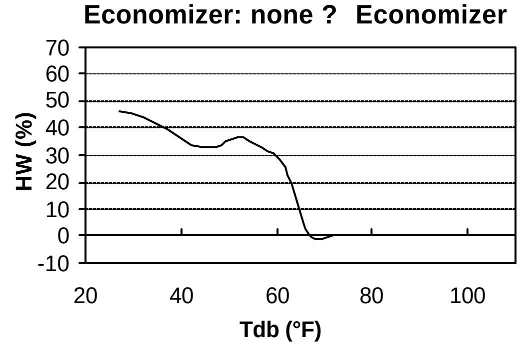
Envelope U-value decreased by 20%



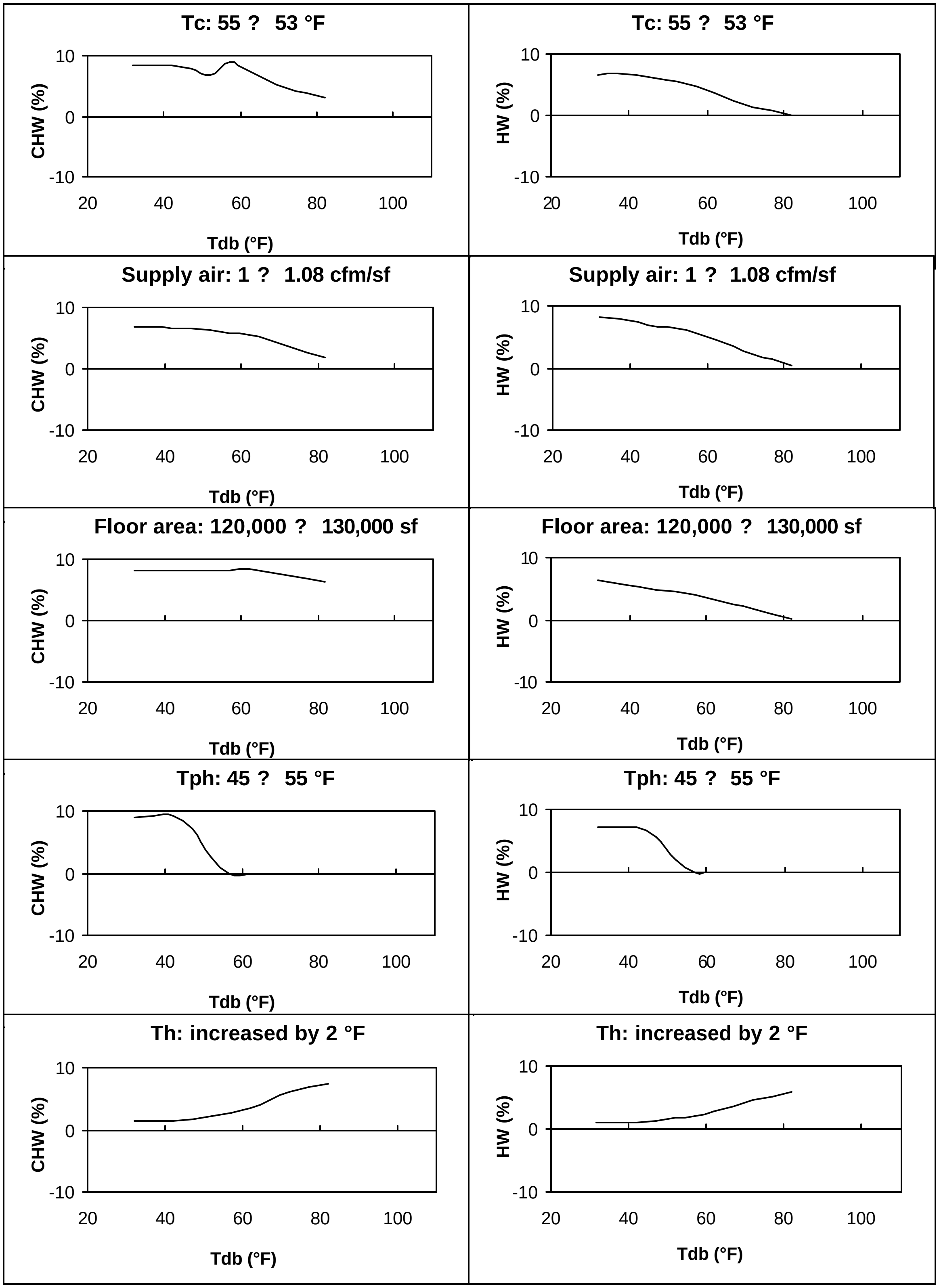
Economizer: none ? Economizer



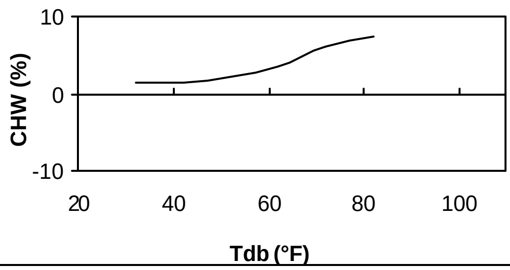
Economizer: none ? Economizer



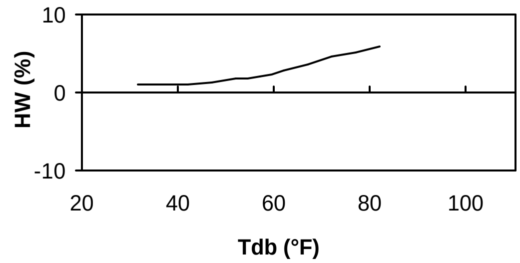
APPENDIX E-3: DDCV SYSTEM IN OAKLAND



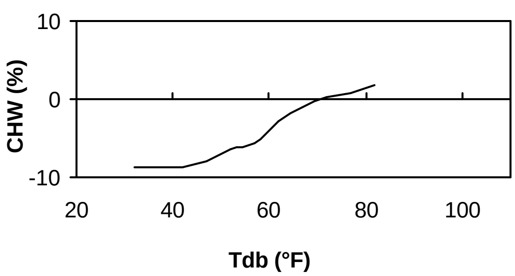
Qint: 1.4 ? 1 W/sf



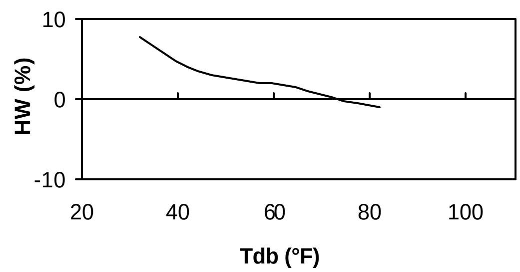
Qint: 1.4 ? 1 W/sf



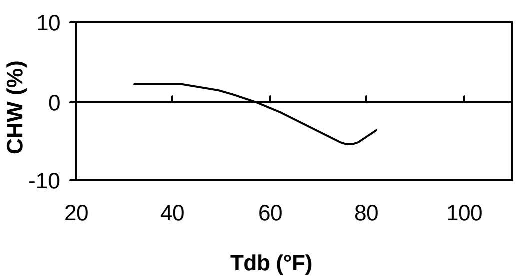
Outside air: 0.15 ? 0.20 cfm/sf



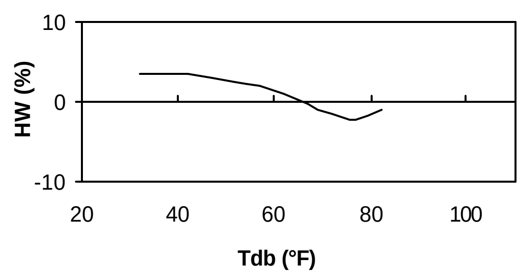
Outside air: 0.15 ? 0.20 cfm/sf



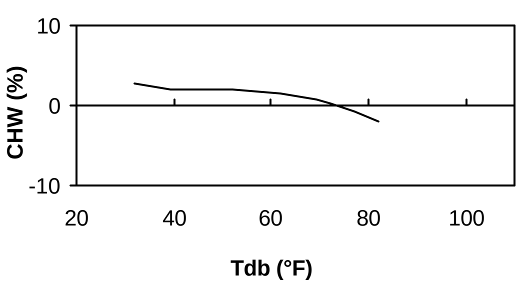
Troom: 73 ? 74 °F



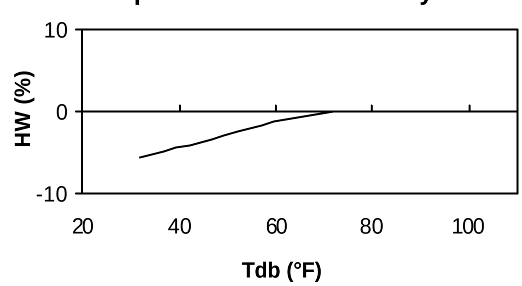
Troom: 73 ? 74 °F



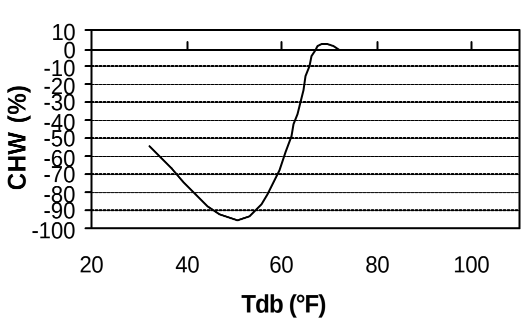
Envelope U-value decreased by 20%



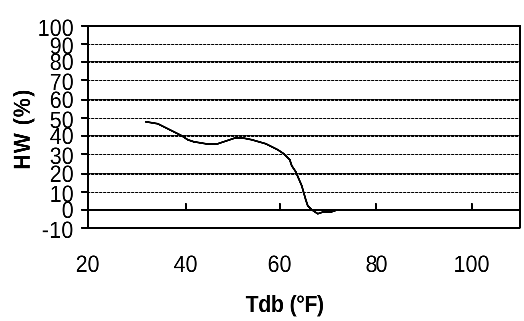
Envelope U-value decreased by 20%



Economizer: none ? Economizer

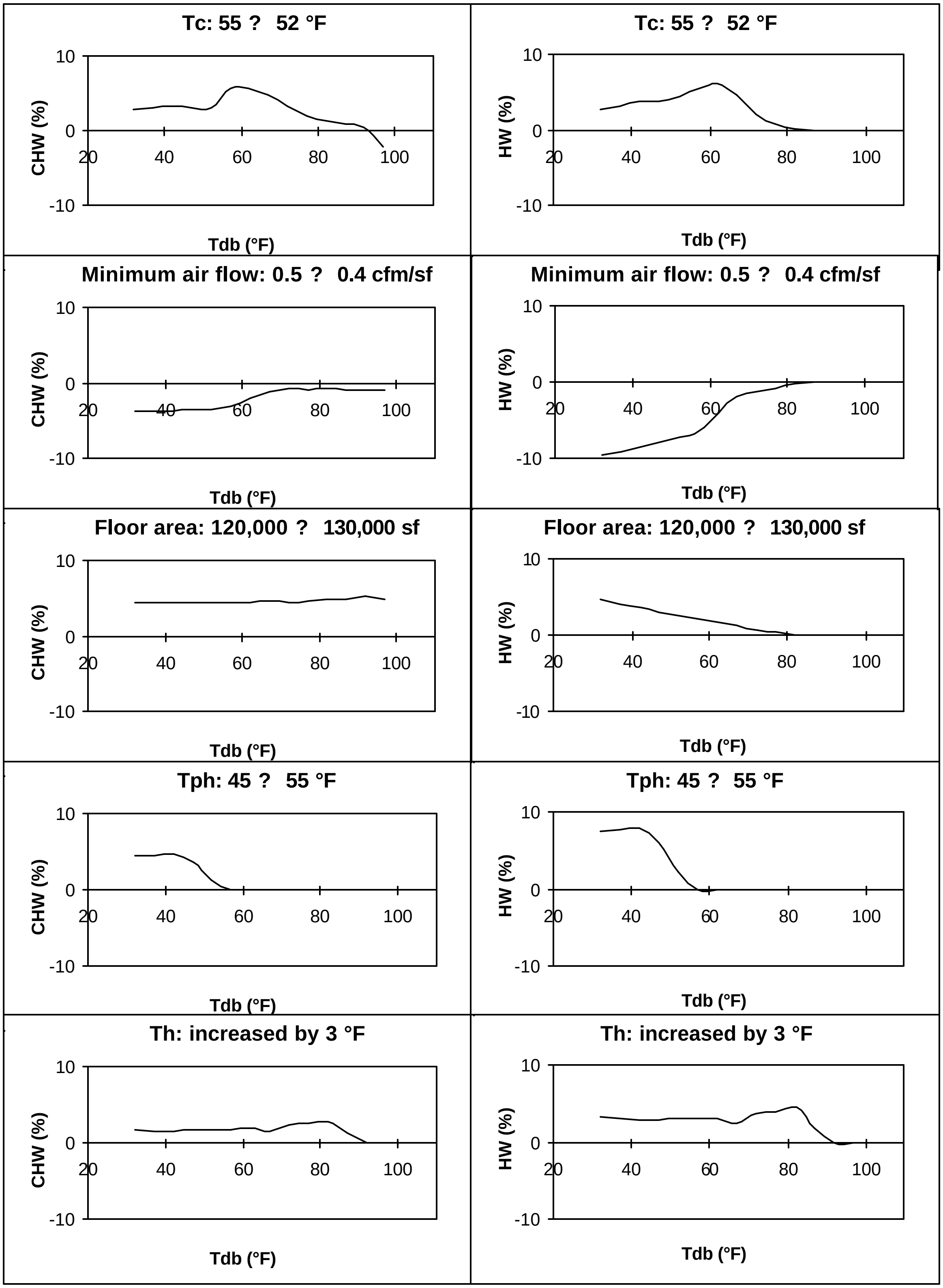


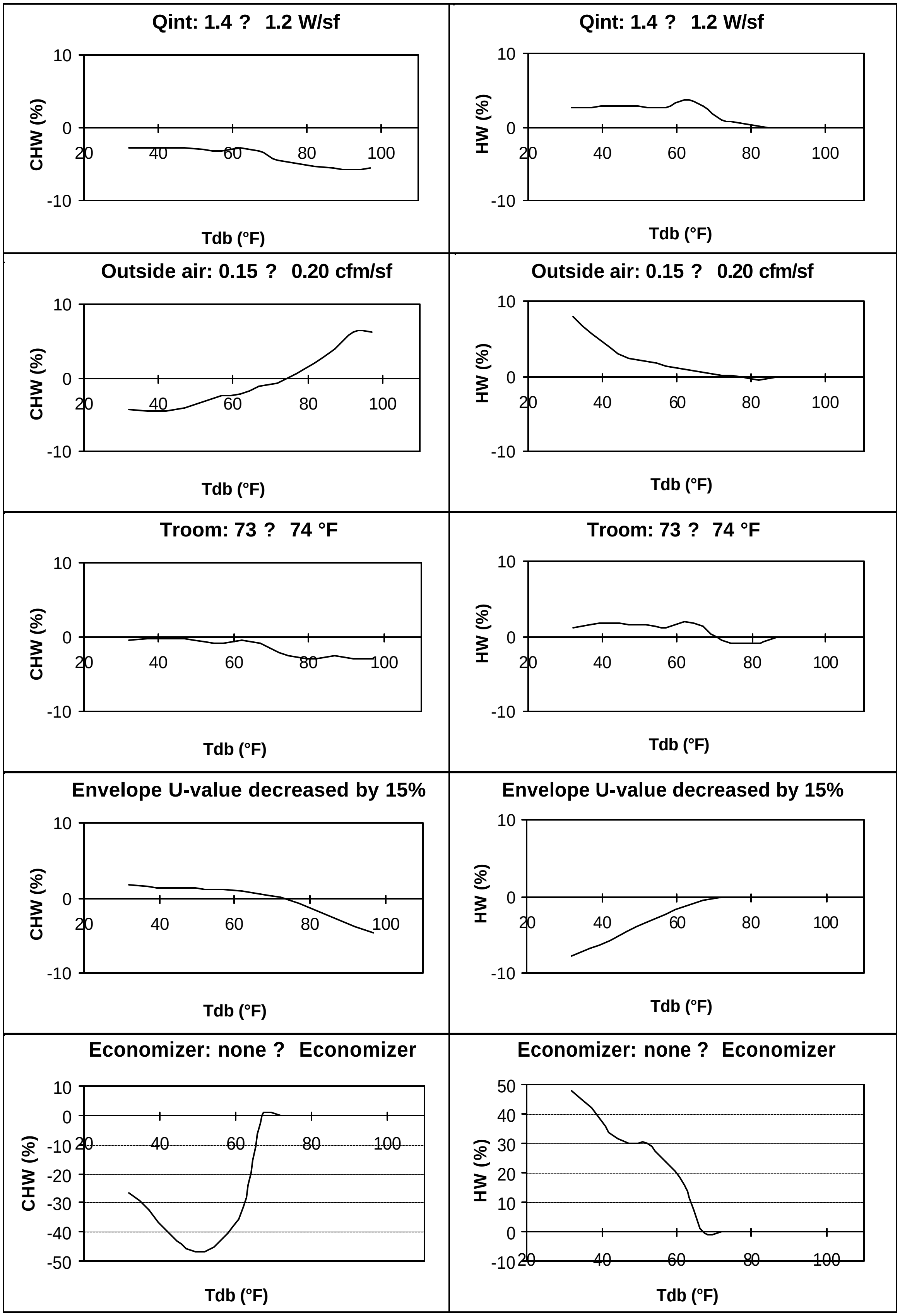
Economizer: none ? Economizer



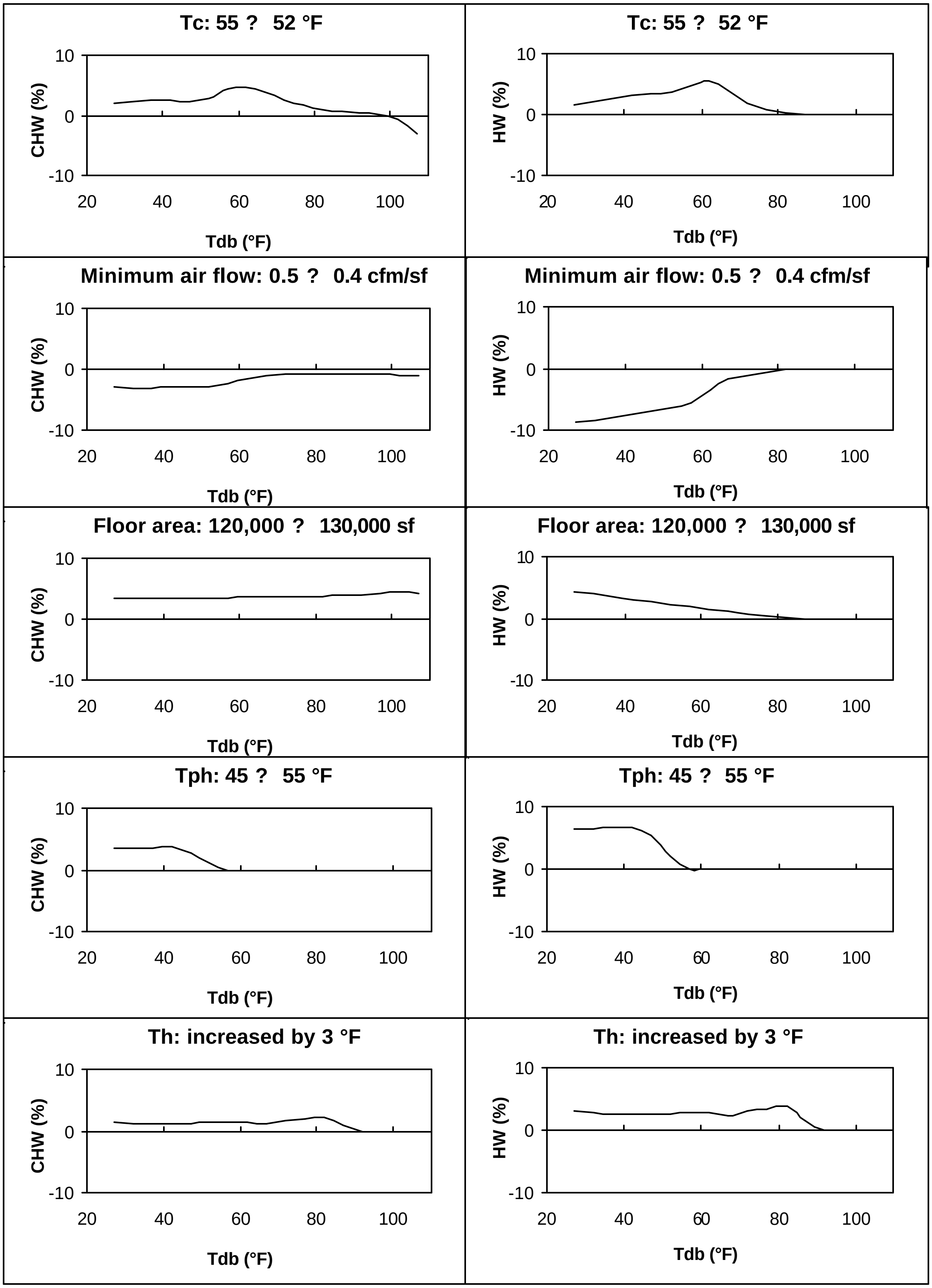
APPENDIX F: CHARACTERISTIC SIGNATURES FOR DDVAV SYSTEMS

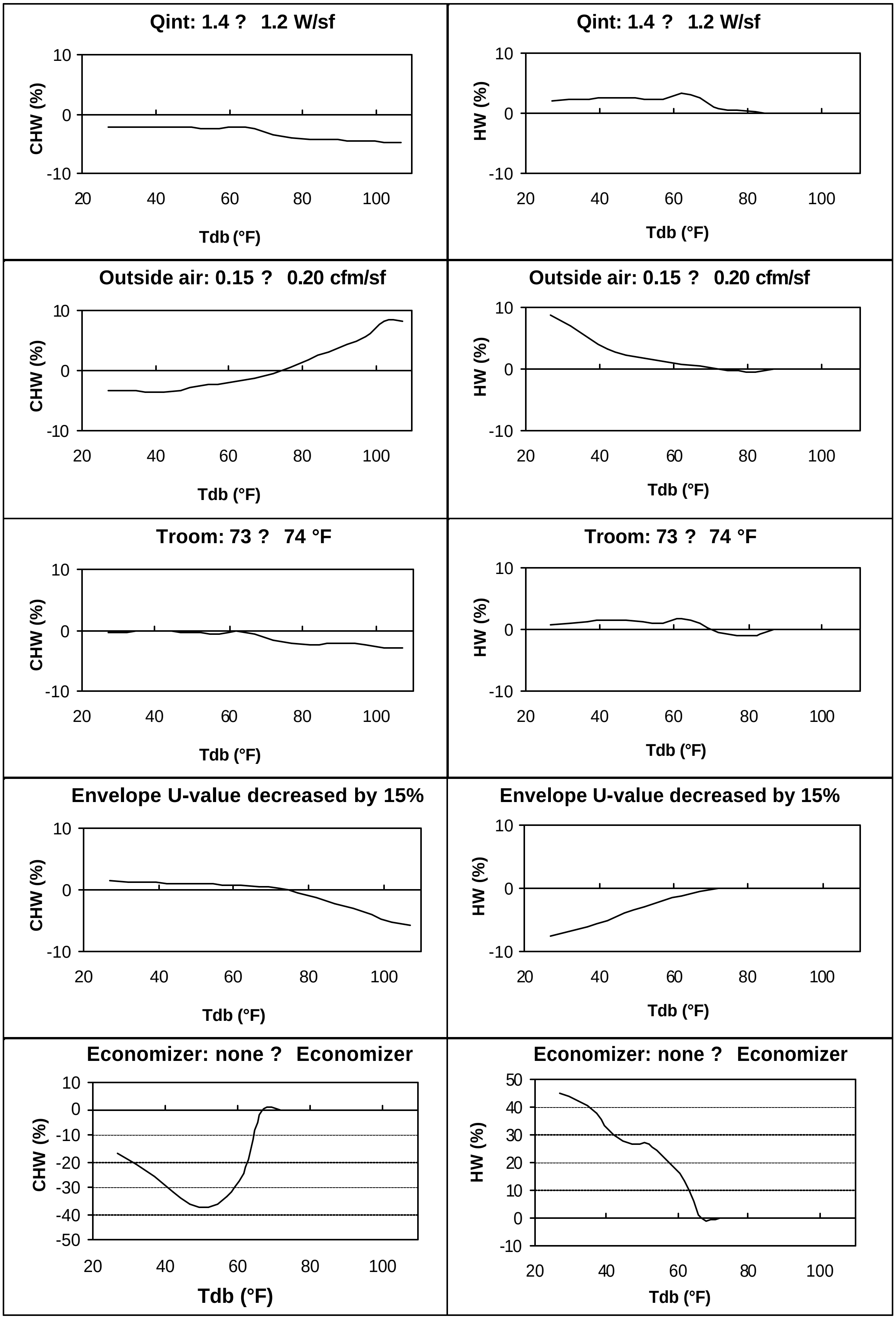
APPENDIX F-1: DDVAV SYSTEM IN PASADENA




Qint: 1.4 ? 1.2 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1.2 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 15%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 15%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

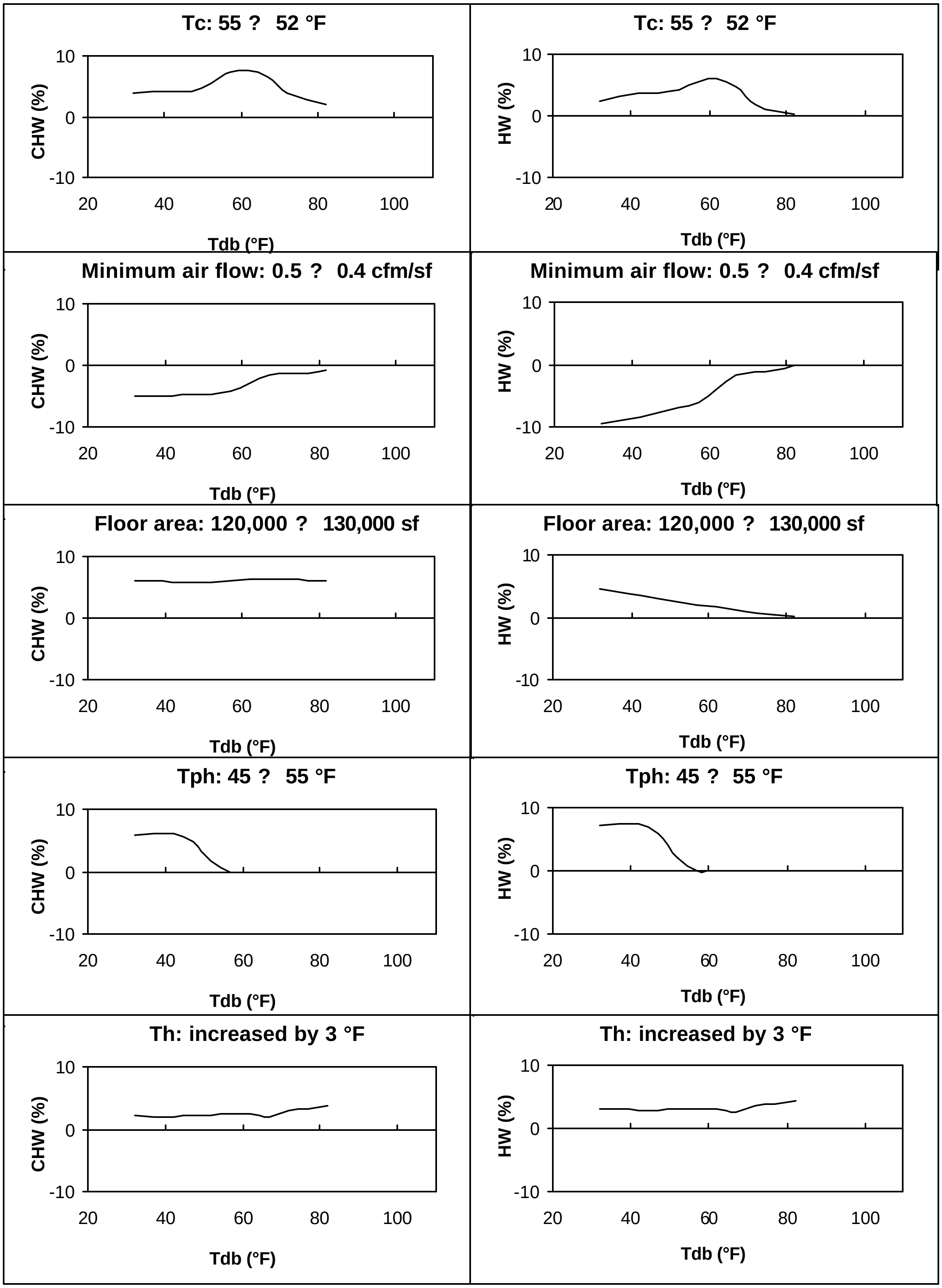
APPENDIX F-2: DDVAV SYSTEM IN SACRAMENTO

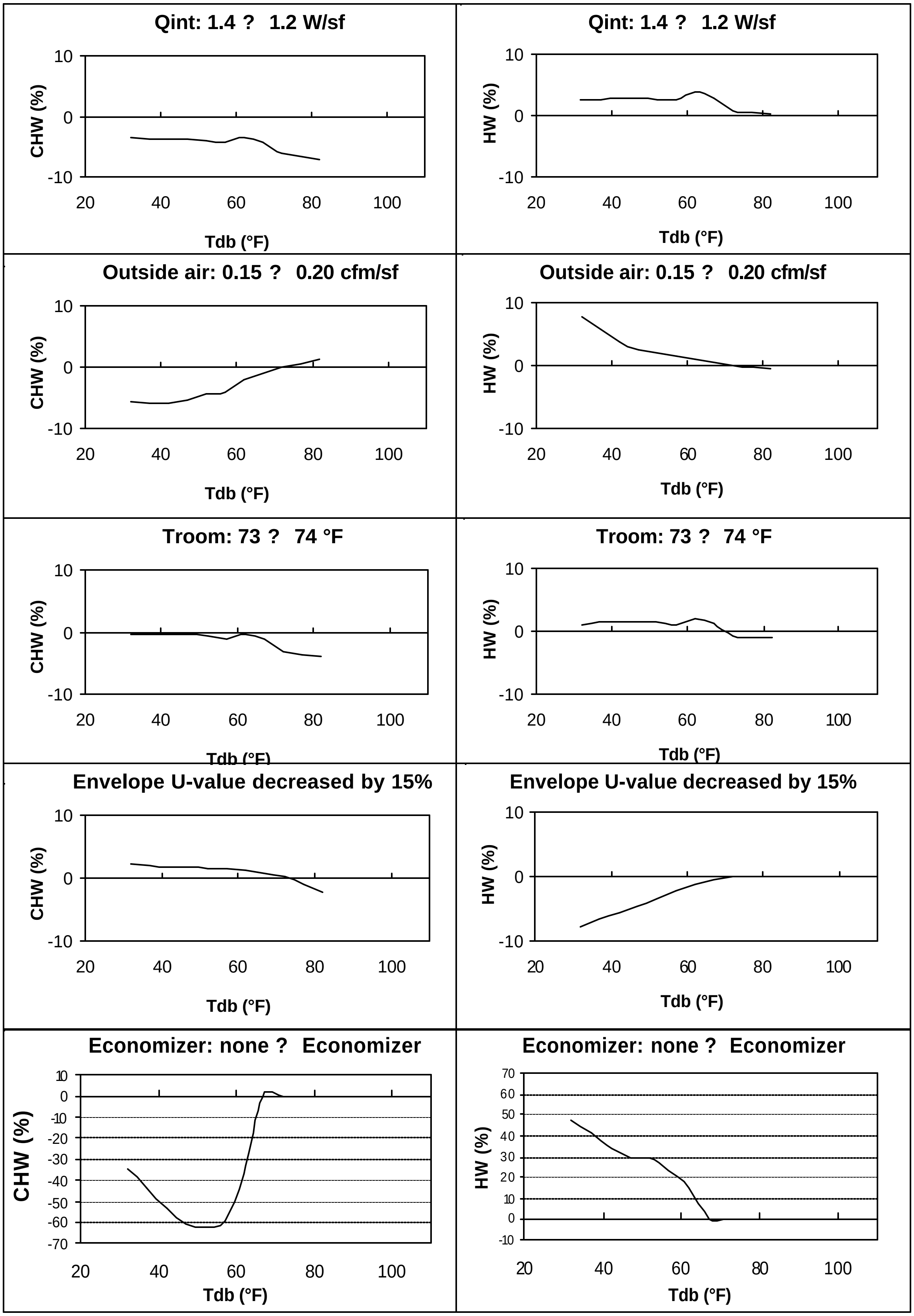




Qint: 1.4 ? 1.2 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1.2 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 15%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 15%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

APPENDIX F-3: DDVAV SYSTEM IN OAKLAND




Qint: 1.4 ? 1.2 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1.2 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 15%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 15%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

APPENDIX G: CREATING YOUR OWN CHARACTERISTIC SIGNATURES

Sets of calibration signatures have been provided in this manual for the four major air handling unit types for three California weather conditions. There may be a need to create one's own calibration signatures for other weather conditions or other variations of air handling unit types, or to test the sensitivity of other input parameters not tested in the provided sets.

It is preferable to use the initial simulation, which is based on the best approximation of input parameters, as the baseline for calibration signatures. Figure G-1 illustrates how a calibration signature is created for an input parameter "ip" using a spreadsheet. MS Excel was used for this purpose.

Any simulation program may be used. Simulated data is then copied and pasted in the spreadsheet to create the signature. In Figure G-1, dry-bulb Temperatures were pasted in column B for the corresponding time steps in column A. Weather data can be hourly, daily… or bin data. The baseline simulation data was pasted in column C with the caption Q_{bl}. It could be either cooling or heating energy consumption. In this initial simulation, the input parameter "ip" had an initial value ip_0. To create the calibration signature for this parameter, its value was altered in the input file from ip_0 to ip_1 and the simulation was rerun. Simulated data was then pasted in column D with the caption Q_p and the calibration signature was calculated in column E for line "i" as:

$$\textit{Calibration Signature for input parameter "ip"} = \frac{Q_{ip}(i) - Q_{bl}(i)}{Max\ (Q_{bl})} \quad x\ 100\% \qquad \text{(G-1)}$$

Max (Q_{bl}) is the maximum baseline simulated value for the whole simulation period. Note that it would be different for cooling and heating. The input parameter is changed to an amount that gives a significant change in energy consumption, typically up to 10%.

Figure G-2 shows the calculation of the cooling calibration signature of the supply air flow rate for a SDCV system. This simulation uses bin data. The baseline simulation was run with a supply air flow rate of 1 cfm/ft^2 and the second simulation was run with a value of 1.08 cfm/ft^2. Signature points were connected with a smoothed line to show the impact of the input parameter over the entire range of dry-bulb Temperatures.

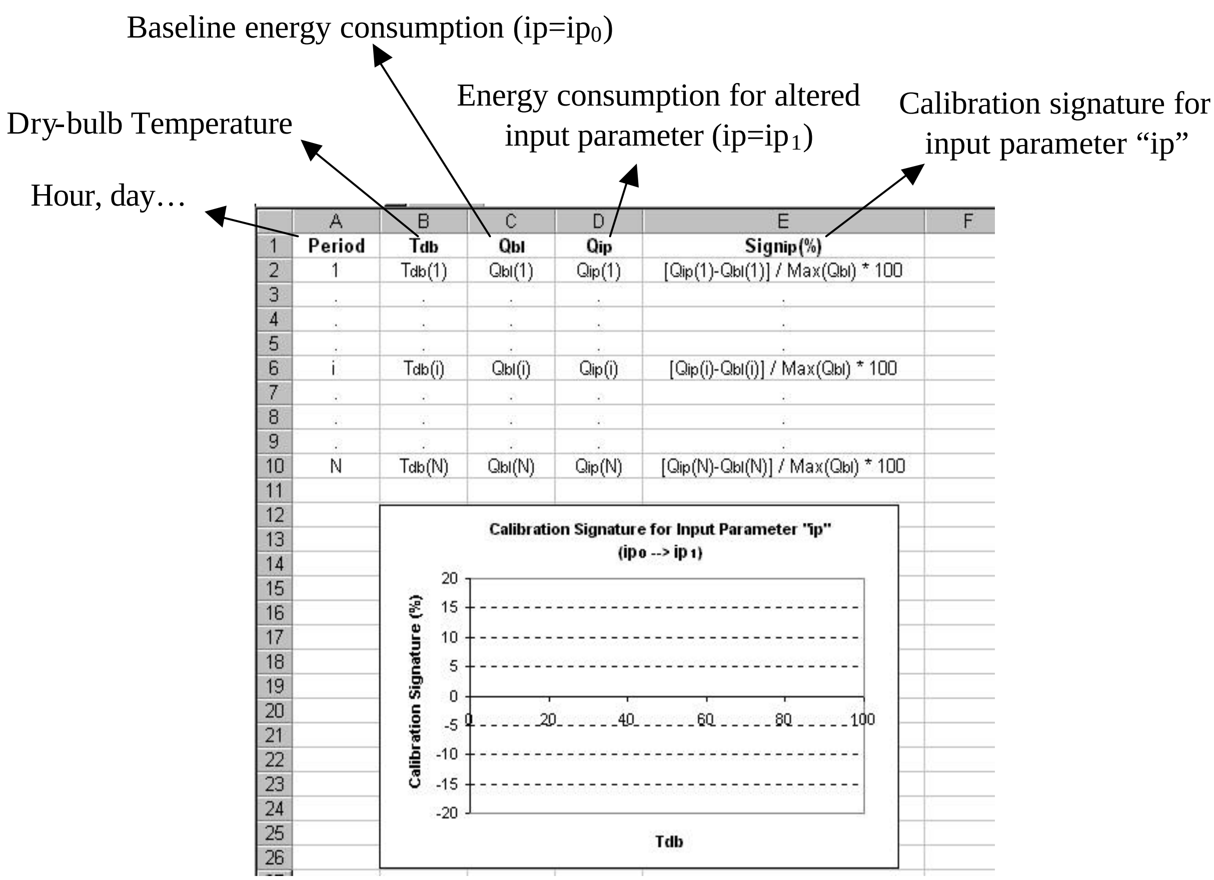


Figure G-1. Creation of the Calibration Signature for Input Parameter "ip"

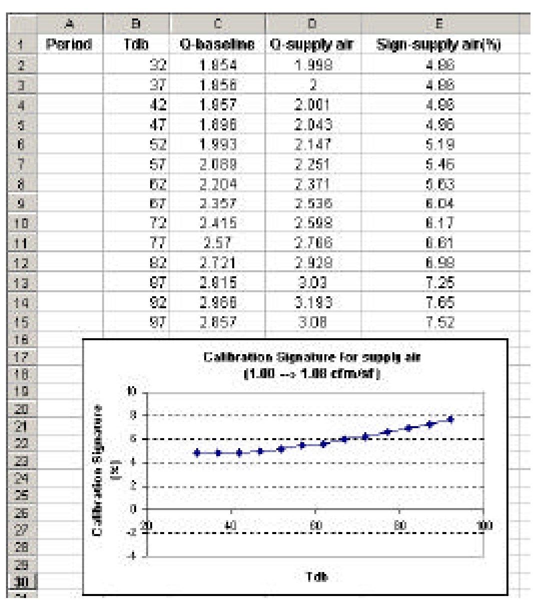


Figure G-2. Calibration Signature of Supply Air flow Rate for a SDCV System